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Technology Assessment for Aircraft Command in Emergency Situations

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16. Abstract

This technology assessment determined the feasibility of FAA support for development of a computer-based system to supplement crew function during in-flight fire/smoke incidents. The system was designated Aircraft Command in Emergency Situations (ACES). It was limited to fire/smoke incidents in areas other than power-plant or lifting and control surfaces. It would be used in large commercial air transports. Thirteen scenarios of in-flight fire/smoke incidents which had occurred or were likely to occur were written to define the events to which a flight crew might have to respond. The responses to each scenario, based on current practice, were described and presented on a timeline. The development of each incident was described as were the significant operational and environmental features. An analysis of each scenario was then made to identify problems encountered in detection and management of the incident. Separate analyses of current sensor technology, aircraft computer/display technology, and of human factors led to a hypothetical ACES system using smoke/heat sensing with determination of rate and extent of change in both. The postulated ACES was incorporated into the master warning concept with advisory displays forced to the cockpit. The scenarios were reanalyzed using the ACES and results compared to the first scenario analysis. It was concluded that an ACES is technologically feasible and can be used in and facilitate air crew emergency procedures. Training will be needed but crew workload will not be negatively affected. In almost every incident the ACES concept significantly reduced reaction time and severity. The continuation of ACES development is encouraged.

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PREFACE

This report describes a study of the feasibility of an automated system that would assist in the detection and management of in-flight fire or smoke incidents. The system is referred to as: Aircraft Command in Emergency Situations, or ACES. It is intended to provide support to the flight crew; it does not preempt any crew function. The ACES study was conducted by Dunlap and Associates, Inc., under contract to the U.S. Department of Transportation; the Federal Aviation Administration (FAA) Technical Center in Atlantic City, NJ, administered the contract and provided technical oversight and guidance.

The Dunlap and Associates, Inc., staff consisted of Richard D. Blomberg, Edward W. Bishop and John W. Hamilton. Mr. Blomberg, the President of Dunlap and Associates, was the principal investigator. This staff was augmented by two special consultants. In addition, many people in the air transport industry volunteered their time and special expertise in support of the study. However, the responsibility for the completeness and the quality of the study rests solely with the Dunlap staff.

Dr. Thor Eklund was assigned by FAA as Technical Officer for this study and was assisted in this role by Mr. Allan Abramowitz. They both provided very valuable guidance as to the conduct of the study as well as a substantial background of information about in-flight fires, relevant research and FAA activities and interests. The quality of the study was greatly enhanced by their dedicated contributions and helpful reviews.

Mr. Richard L.P. Custer, an Associate Professor of Fire Protection and Mechanical Engineering at Worcester Polytechnic Institute, was a consultant to this study from its inception. He helped in planning and in all subsequent phases of the study; he authored those parts of the report which concern fire propagation and sensor technology.

Mr. Norman R. Parmet, who retired as Vice President of Engineering of TWA, was a consultant throughout the study. Mr. Parmet is an airline industry consultant and participates in aircraft accident investigations. He is also Vice Chairman of the NASA Aerospace Safety Advisory Panel. He provided special help with regard to air crew functions and operations, and provided guidance for the overall conduct of the study. He was instrumental in gaining airline cooperation.

The cooperation of several people in the air transport industry was very generously given. Many of these were in direct contact with the study staff but they were also supported by others in each organization. In order to avoid any inadvertent omission of any of these advisors, we will list below only the organizations with which they are affiliated. The contribution of each one was essential and valuable to the study. A very grateful acknowledgment is extended to these organizations and their staffs:

- o Aeronautical Radio, Inc.
- o Airbus Industrie
- o American Airlines
- o Boeing Commercial Airplane Company
- o Douglas Aircraft Company
- o National Transportation Safety Board
- o Trans World Airlines
- o United Airlines

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES AND TABLES

LIST OF FIGURES AND TABLES (Continued)

EXECUTIVE SUMMARY

This study was performed by Dunlap and Associates, Inc., under Contract DTFA03-87-C-00020 for the Federal Aviation Administration (FAA) Technical Center. It had its origin in the Center's concern for the detection and control of in-flight fire and smoke incidents. The purpose of the study was to conduct a technology assessment to determine whether the feasibility exists for FAA to support development of a computer-based cockpit system for assisting aircraft command in emergency (in-flight fire/smoke) situations. This system, which would supplement and facilitate the crew response, is referred to as ACES. The technology assessment of ACES was defined to include only in-flight fire and smoke incidents not originating in an engine or flight control surfaces. It was further limited to commercial transport aircraft in regular (non-commuter) airline service. The application of ACES was to be considered only for new aircraft, not for retrofit.

This study was designed around the development and analysis of a set of scenarios which describe in-flight fire and smoke incidents that had actually occurred or that could reasonably be expected to occur. Thirteen such scenarios were produced: four based on actual events which had been investigated in detail and nine based on incident reports or on potential incidents of special concern to the industry. The scenarios were written without identification of aircraft model, and no company or individual names were used. For those based on actual events, the locale was changed to further assure anonymity. The 13 scenarios that were developed range from a catastrophe in which the more than 300 persons on board perished and the aircraft was completely destroyed to a minor overheating of a light ballast. False alarms are also included. These 13 scenarios, then, are a realistic representation of the universe of events to which a flight crew, using an ACES system, could be expected to respond.

The technology to support an ACES system was examined in two broad areas: sensor technology (existing or projected) to provide the information required to cope with the anticipated incidents; and computer and display technology by which the ACES interface with the cockpit crew would be implemented. In addition, the human factors and crew workload involved in reacting to and using the ACES system were assessed.

A bascline for feasibility assessment was established by analyzing the problem faced by the crew in each scenario and describing the crew response under current procedures. This was done on a timeline showing the evolution of the incident as well as the crew responses and effects. This analysis was carefully reviewed to ensure that the baseline accurately reflected what had actually occurred or what would have occurred in the case of the adapted scenarios.

In parallel, a hypothetical ACES system was postulated. It includes the sensing of both smoke and heat as well as the determination of rate and duration of change in both. It provides monitoring and adjustment of its own system sensitivity and operational status. The ACES interface with the crew is incorporated into the existing master warning concept, and appropriate advisory emergency procedure information is "forced" to a cockpit display. This

conceptual system also has access to "circumstantial evidence" such as electrical and hydraulic system status. All of these features are within the current state of each of the technologies and no development of new technology is required.

Each of the scenarios was then analyzed a second time assuming that the ACES concept had been available and applied.

The outcomes of this study are summarized in the following conclusions:

1. An ACES, as conceptualized, is well within the current (or very near future) state of sensor, computer and display technology.

2. Appropriate and adequate human participation in the ACES concept is both feasible and practical. Specific human factors design and training issues will have to be addressed, but these present no impediment to ACES implementation.

3. The analysis of current operations suggests that evaluation and interpretation of current alarms and indications (such as smoke source) by the crew is extremely time consuming, often erroneous and at odds with the only essential response, which is to land the aircraft as quickly as possible.

4. The crew response to the current system, including evaluation and interpretation, tends to increase workload which is further exacerbated when the crew persists in erroneous conclusions (as has often happened).

5. Crew workload is not negatively affected by the requirements of the ACES concept.

6. A common characteristic of crew responses in the current situation is a reluctance to accept smoke/fire warnings. Presumably, this results from experience with unreliable sensors and perhaps from an unwillingness to acknowledge a potentially catastrophic event. This represents a human factor to be considered in ACES implementation.

7. In virtually every ACES analysis, the scenario would have been resolved more quickly and the outcome would have been less catastrophic had the conceptual system been applied.

8. ACES implementation from a technological viewpoint is essentially a continuation of current development activity. Operationally, this implementation will require special attention to system integration and crew attitude toward and acceptance of the ACES concept.

INTRODUCTION

This is the final report of contract number DTFA03-87-C-00020 between the U.S. Department of Transportation, Federal Aviation Administration (FAA) Technical Center and Dunlap and Associates, Inc. The study reported herein is entitled "Technology Assessment for Aircraft Command in Emergency Situations."

OBJECTIVES.

Recent developments in aviation have provided both new opportunities and new requirements in various aspects of flight management. These developments have potential additional impact on detection and control of hazards arising from in-flight fire and smoke incidents. The purpose of this study was to conduct a technology assessment to determine whether the feasibility exists for the FAA to support the development of a computer-based cockpit system to assist aircraft command in emergency situations (ACES). The technology assessment was to address the state-of-the-art of in-flight fire sensing and management, and of cockpit computer and display technology for interfacing with the aircrew through diagnostic and prescriptive information.

The boundaries of the ACES feasibility study were defined to include only:

1. In-flight fire and smoke incidents exclusive of lifting and control surfaces and propulsion plants;

2. Commercial, regular airline (as opposed to commuter) transport aircraft;

3. New aircraft designs rather than retrofits to existing aircraft.

In order to achieve the overall purpose of the study, the following four questions had to be answered:

1. What information is needed to locate and monitor fire and smoke sources?

2. Is the sensing capability available or attainable?

3. What courses of action can be employed in reaction to the sensed information?

4. Within constraints of cockpit technology anticipated for future commercial transport aircraft, can this information be computerized and retrieved in a fail-safe manner?

The pursuit of answers to these questions led directly to the major tasks of the study. These were:

Problem analysis and fire scenario development. The contract specified that 10 scenarios, primarily concerned with fires of an inaccessible nature, were to be developed. As work progressed, it was clear that more than 10 would be needed to describe the full range of actual fires and false alarm events with which an ACES would have to deal. The final set of 13 scenarios were used to guide the remainder of the work effort.

Sensor identification and analysis. The ability of existing sensors to cope with the fire/smoke incidents described in the scenarios was assessed. In addition, the applicability of emerging sensor technology to the defined problems was also examined. The objective of this effort was to identify the means for sensing valid information which would be accurate, reliable and consistent with the mission of an ACES.

Cockpit resource analysis. The ability of existing and potential cockpit computer, display and warning systems to handle information related to the management of fires was studied.

Crew interface analysis. Crew human factors, particularly workload, under the demands of the 13 scenarios was assessed to determine the ability of the pilots to use effectively the information provided by an ACES system.

Feasibility assessment. The information from all of the various analyses was integrated using appropriate methodologies in order to reach conclusions concerning ACES feasibility.

The specific approach to each of these tasks is covered in detail in the next section of this report. This is followed by a description of a hypothetical ACES system. Following that, each of the 13 scenarios is presented including the application of the ACES concept as a test of feasibility. The report closes with conclusions concerning the feasibility, benefits and possible uses of an ACES system designed in accordance with the proposed concepts.

BACKGROUND.

THE PROBLEM. There are few events in aviation which conjure up more fear and feelings of helplessness than in-flight fires. The notion of being in command of a commercial jet transport carrying over 350 people at 35,000 feet over the Atlantic which experiences a fire in a hidden space is universally chilling to airmen. Obviously, the prevention of such fires is of paramount importance to the safety of civil aviation. The air transport industry as well as regulatory agencies have focused a substantial effort on fire prevention, and the design of modern transports does much to minimize in-flight fire hazards. As a result, the incidence of in-flight fire and smoke in the cabins of jet aircraft is quite small relative to overall flight operations (Lorengo and Porter, 1986).

In spite of the best prevention efforts, in-flight fires do occur. Hence, ways to manage and control them and reduce their severity, particularly with respect to loss of life, are warranted. These efforts can productively focus on the detection of fires and their containment or suppression. Coupled with the need for rapid detection of real fire or smoke events is the need to eliminate false alarms. Simply, once the crew of an aircraft in flight declares an emergency and takes appropriate actions up to and including a diversion and emergency evacuation, risk to the persons on board increases. There are also obvious negative impacts to an air carrier from emergency evacuations, especially if they prove to be false alarms. It is almost impossible to evacuate a transport aircraft without some injuries to passengers arising from the escape process.

There is a great potential for disaster whenever an in-flight fire occurs. Therefore, there is little interest among airlines, pilots or regulatory agencies

in a system which would deal with a fire during flight and allow the plane to continue to its planned destination. The strong consensus is that the only viable countermeasure to a confirmed in-flight fire is an immediate decision to land at the nearest suitable airport. Thus, the ACES concept incorporates this response as its primary, inflexible parameter. Other practical countermeasures or suppression activities are included as secondary parameters.

In order to achieve the desired response, an acceptable ACES would have to concentrate on the rapid detection of fire and smoke events, the determination of their severity, and the discrimination of real events from false alarms. This would permit the crew to minimize the time between the onset of a real event and the time the aircraft is on the ground at a suitable airport. It would also provide the maximum amount of time for analyzing and choosing a suitable field.

The concern with in-flight fires in the U.S. commercial fleet focuses primarily on their potential for catastrophic events. Most of the reported in-flight fires in the FAA data bases are relatively minor and do not even involve a change in flight plan. Lorengo and Porter (1986) identify 1,274 "cabin/cockpit in-flight fire and smoke incidents" for the years 1979 through 1985. Only 290 of these involved an unscheduled landing or emergency descent. Over the same time period, however, there were two major in-flight fires with resultant fatalities. In 1980, a Saudi Lockheed L-1011 Tristar experienced an in-flight fire and, although it managed to return and land at Riyadh, its departure point, all 301 people on board died. In 1983, an Air Canada DC-9 en route to Toronto, Canada, from Dallas, Texas, caught fire and eventually diverted to the Greater Cincinnati International Airport. Twenty-three of the 46 on board perished.

The potential dangers of in-flight fires are compounded by the presence of combustible material in several areas of a modern transport which are essentially inaccessible during flight. Large underfloor cargo compartments, miles of wiring and hydraulic lines buried in cheek, underfloor and attic spaces and extensive electronic racks in avionics bays are all areas in which in-flight fires may start and burn undetected until they are sufficiently large as to present a serious threat to aircraft systems and occupants. These types of fires represent a greater concern than those which begin in the cabin itself as a result of, for example, smoking, overheated light ballasts or galley accidents. Accessible cabin areas are typically well populated by human "sensors" who provide early detection. Such fires can then be dealt with by cabin or flight crew members before they become severe.

Finally, it must be noted that the air conditioning/pressurization system which is so important to the comfort and well being of the inhabitants of a modern transport can also be a source of cockpit and cabin smoke. The old adage that "where there's smoke there's fire" is not strictly true in an aircraft. Smoke can be generated within the air conditioning packs or ingested from the outside of the aircraft and distributed throughout the cabin and cockpit by the air conditioning system even in the absence of a fire. Because of the dangers inherent in high smoke concentrations in a confined space, smoke events are very much a focus of interest in this study. In fact, as the reader progresses through this report, he or she should keep in mind that all references to "in-flight fires" are intended to include fire and/or smoke events unless specifically noted to the contrary.

EXISTING APPROACHES. The modern aircraft cockpit and crew interface is designed around a master warning concept. Under this approach, subsystems of the aircraft have built-in tests for anomalous conditions. When these exist, a master warning horn or gong is sounded in the cockpit. This alerts the pilots that a problem exists and cues them to start scanning their displays to determine the source of the trouble. In the case of a few very special situations which require a virtually instantaneous response from the crew, a unique auditory warning is used rather than the general master warning sound. This unique warning is typically a synthetic voice issuing a command. The "PULL-UP" message of the Ground Proximity Warning System (GPWS) is one example of this approach.

The very latest generation of aircraft including the Boeing 757/767 and the Airbus Industrie A310 and A320 are characterized by a "glass cockpit" and digital data bus systems. The glass cockpit derives its name from the use of multiple cathode ray tube (CRT) displays for the presentation of primary flight data (attitude, airspeed, etc.), navigation data and system status. The extension of the master warning concept to the glass cockpit involves the use of a standard alerting signal and the presentation of a description of the failure or emergency on one of the system status CRTs.

The response of the crew to a warning depends on its nature and severity. Many of the activations of the master warning are "anticipated." That is, the crew understands immediately that the warning has gone off because of something they intended to do or because of something which just happened and of which they are aware. In most aircraft, for example, an autopilot disconnection will activate the master warning.

When a master warning is for a systems problem or emergency, the crew will typically refer to a standard checklist for handling the problem. The location and use of this checklist will vary somewhat as a function of aircraft type. On the older, conventional aircraft the checklist is always printed. It is generally found in the flight crew operating manual (FCOM) which is carried on board. It may also exist in a quick reference version placed within easy reach of the pilots (often on the glare shield). The quick reference checklists are usually those used most frequently, e.g., takeoff, landing, and those which are most time critical, e.g., emergency evacuation.

Some of the newer high automation aircraft, e.g., the Airbus A310 and A320, display the checklist along with the description of the problem on the systems CRT. This appears to be the trend in the industry for future aircraft designs. It also is an approach which pilots like because it reduces the need to locate the FCOM or quick reference checklist and then find the appropriate pages within it. Boucek, Berson, Summers and Hanson (1985) found that pilots generally wanted both warning and caution checklists to be displayed automatically.

The issue of fires, particularly in hidden spaces on transport aircraft, is addressed in quite different ways across the existing commercial fleet. Lower cargo compartments in large transport aircraft are categorized as either Class C or Class D types. Class D compartments are typically small compartments designed to contain a fire by oxygen starvation. Class C compartments tend to be larger and are required to have a fire detection and suppression system (Sarkos, 1985).

The installations in Class C compartments typically consist of smoke (aerosol) detectors which are connected to a fire warning panel in the cockpit. The initial alert to the crew is through the master warning horn. In order to reduce false alarms arising from sensor failures, most systems currently being installed employ two sensors at each location connected logically by an "AND" gate, i.e., both sensors must trip to produce a warning. Other implementations have the two sensors in separate loops connected so that if one sensor trips, a caution is sounded and if both trip, a warning is issued.

The typical smoke sensor used in current installations is a photoelectric device. These operate on the principle of light scatter due to the particulate matter in the air. A photocell is placed at right angles to a light source within a confined space. In the absence of a significant concentration of particulate matter, little light reaches the photocell and its voltage output remains low. If the level of aerosol particulates increases, the light is scattered to the photocell and its voltage output increases. When this output reaches a predetermined threshold level, the sensor trips. The sensor is not specific to airborne combustion products. Anything which enters the chamber and will scatter light (e.g., water condensate, can generate an alarm).

As a result of several lavatory fire events and to meet the requirements of Federal Airworthiness Regulations (FAR) 121.308 and 121.185, smoke detectors and automatic extinguishers in trash receptacles have been installed in aircraft lavatories. In virtually all of these retrofits, the detector is not connected to the cockpit alarms and warnings. Rather, a visual and aural warning is sounded in the cabin, usually by activating the attendant call system in the lavatory. Some of the newer aircraft produced after these requirements became effective relay the notice directly to the cockpit that the lavatory smoke sensor has activated.

Cabin suppression systems consist of hand fire extinguishers as well as the automatic ones in the lavatory trash bins. Cargo and avionics area suppression systems for Class C holds are normally two bottles of Freon or Halon gas which can be discharged into any of the cargo holds. If a warning is issued from a Class C sensor, the Flight Crew follows a checklist to isolate the involved compartment from the ventilation system and discharges the first bottle. The second bottle is discharged about an hour later if the flight has not yet terminated.

The human element is an important part of the management of in-flight fires. First, human detection of fires has traditionally been the primary mode by which the crew becomes aware of the problem. For example, Lorengo and Porter (1986) report that only 146 (11%) of 1,274 in-flight fire and smoke incidents occurring between 1979 and 1985 were accompanied by a sensor or alarm warning. It is presumed that the balance and vast majority of the fire or smoke events were recognized by human "sensors." In fact, the battery of human sensory mechanisms is quite good at detecting the products of combustion once they reach a threshold level. The problem is that humans typically occupy only about half of the volume of a modern jet. A small fire in the remaining, "hidden" fuselage areas can grow to a significant size by the time a human can detect it.

Humans also are a critical element in fire management systems because they must interpret and act upon warnings they sense or those provided by

automated systems. As will be illustrated in the developed scenarios, many in-flight fire or smoke events are made more severe by the reluctance of the flight crew to believe existing warnings and take appropriate actions. Even though the standard operating procedure in the airline industry is to land at the nearest suitable airport whenever a fire warning activates, experienced pilots have deliberately delayed landing while attempting to confirm automated warnings.

Some of this aberrant pilot behavior is likely accounted for by the relatively high false alarm rate experienced by many existing sensor installations. In addition, most people (including pilots) do not have a complete appreciation of the mechanism by which fires propagate and, hence, of the limited time available to respond. Human fallibility, particularly under stress and associated high workload must also be considered.

THE ACES CONCEPT. The foregoing discussion of the current situation is not intended as a detailed treatise on existing regulations or practice. Rather, it is intended to provide a basis for the postulation of a new system, ACES, which has the potential to yield a marked improvement in performance. The areas in which an ACES system is expected to provide significant improvement are:

1. Sensing - There clearly is a need for improved sensing of in-flight fire and smoke events. A reduction in false alarms, more rapid discrimination of real events and an extension of sensing to more areas of the fuselage could all have potential benefits.

2. Alerting - Flight crews generally are notified as soon as a fire is detected by persons on board or by an automated system. Therefore, there is not a great potential for improving the speed of notification once detection has occurred. However, the quality of the information concerning the nature, severity and location of the fire can be greatly improved.

3. Crew response - It would appear that much time is lost during the resolution of an in-flight fire event in retrieving and following checklist procedures. Thus, a benefit should be forthcoming from a system which reduces this response time while preserving or improving accuracy.

4. Crew decision making - Problems are created when the crew does not accept information from existing systems. Further, the available information is often incomplete and as a result crews make faulty decisions which also delay the application of appropriate countermeasures. If a new system proves reliable, crew confidence should increase, and situations in which the crew wastes time seeking confirmation of the existence or extent of a fire should be reduced.

These focal areas help define the boundaries for postulating an ACES system and assessing its feasibility. They also suggest that the time between the outbreak of the fire or the generation of smoke until the aircraft is on the ground and all occupants are evacuated should be a primary criterion in examining alternative approaches. Simply, the faster an aircraft involved in a fire or smoke incident is out of the sky, the less time the fire has to propagate and generate hazardous by-products.

The next Section of this report will detail the various study activities which provided the input information needed to define a prototype ACES system for in-flight fires and assess its feasibility.

METHOD

The approach adopted for this ACES system technology assessment was scenario-based. Under this approach, in-flight fire scenarios played two important roles. First, they were the basis for defining the "universe" of fire and smoke events that the hypothetical ACES system would have to address. As such, they formed the input information needed to describe the properties of an ACES system which might prove productive in dealing with the problem. Second, they provided a testbed against which proposed ACES designs were assessed. Examinations of each of the scenarios with and without the application of the ACES system provided the basis for judging both the potential for help and the likely extent of assistance the concept could provide.

The importance of the scenarios in the study approach dictated the need to exercise great care in their preparation. The set of scenarios had to represent a reasonable cross section of actual in-flight fire or smoke events in order to serve as a basis for ACES design. Further, each scenario had to be realistically and accurately portrayed to facilitate the assessment of ACES feasibility.

The steps which were undertaken to implement the approach began with an analysis of the in-flight fire problem. This defined the universe of situations which would be studied and the general content of each scenario. It also led to a generic "model" of the in-flight fire process which could serve as an outline for scenario development and analysis.

Since it was clear that automatic sensing of combustion products had to be an inherent part of any ACES design, an analysis of the state-of-the-art of sensor technology was undertaken in parallel with the study of the problem. Similarly, it appeared certain that computer support would be needed for an ACES system and that some method of alerting the crew would be required. Therefore, these two areas were also studied in some detail.

How each of these tasks or sub-studies was conducted will be discussed in the remainder of this section concluding with a presentation of the scenario development process.

PROBLEM ANALYSIS.

In the context of a study such as this, it is typical to search for problems with the highest frequency of occurrence and/or the greatest severity in terms of fatalities and injuries. This was accomplished by reference to the literature and by searching the FAA's data bases of Service Difficulty Reports (SDRs) and the Accident/Incident Data System (AIDS).

Initial contacts with the literature and data bases suggested that more information would be required. There are relatively few events involving in-flight fire or smoke. Lorengo and Porter (1986) report on a thorough search of

existing data. They tallied a total of 1,951 reported incidents during the years 1964 through 1985. That is a rate of only about 88 events per year. In addition, they reported that many of the data sources were incomplete or overlapped. To place this frequency in context, Starrett, Lopez, Silverman, Susersky and Logan (1976) reported that the rate of in-flight fires associated with an injury or fatality between 1964 and 1974 was approximately 0.1 per million departures. Even considering only incidents (those events which result in damage to the aircraft but not necessarily loss of life or serious injury), the rate reported is only 14.9 per million departures.

It was also clear from an examination of the data bases and summaries of events that more detailed information would be needed to support scenario development. It is not sufficient to know, for example, that a fire occurred in a cargo compartment and resulted in a loss of life. In order to assess the ACES, it was necessary to determine with some degree of accuracy the chronological events beginning with the start of the fire and ending with its resolution as an accident or incident.

Analyses and anecdotal reports from aircraft manufacturers and airline personnel suggested that detailed data of the type needed could best be obtained from two sources. The first was the aircraft accident reports produced by the National Transportation Safety Board (NTSB) based on its investigations. NTSB's inquiries and, hence, its reports are often quite detailed and delve into all aspects of an accident. Unfortunately, the level of detail in the NTSB reports is directly related to the severity of the accident. After major events characterized by significant loss of life, the NTSB report contains all of the detail needed for the development of a scenario and the definition of the event timeline for the accident. For incidents or accidents with minor consequences, the NTSB reports are more sparse and typically do not contain all of the information upon which to base a scenario.

The second source of data was operating airlines and major airframe manufacturers. These groups maintain excellent records on all of the incidents surrounding the operation of their fleets. Their internal reports, even for a relatively minor incident, can be quite complete. Although these data are typically not available to the public, excellent cooperation was received from all of the airlines and airframe manufacturers approached during this study.

During the compilation of accidents and incidents from the literature, FAA, NTSB and industry sources, it became clear that false alarm events were also a problem and source of concern. The consequences of a false fire warning can be quite severe. If a false warning is totally accepted as real by the flight crew, it can lead to an emergency landing and evacuation of the aircraft. This often results in injuries during the emergency egress from the aircraft. Even if the crew suspects a false alarm and merely diverts the flight without an emergency evacuation, there are undesirable consequences. At the very least, an airline's public image is marred by the inconvenience and emotional upset suffered by a plane load of people making an unscheduled landing.

Three distinct types of fire or smoke events in addition to false alarms emerged from the problem analysis. The first were the major disasters resulting from in-flight fires. Documentation of these events was extremely thorough by the NTSB or other investigating agency. Since these events had actually happened and claimed significant numbers of lives, it appeared reasonable to fashion scenarios based on them.

The second type of event included incidents (or potential incidents) in the concealed or "hidden" areas of the aircraft. Information about these was more speculative than the major accidents and not as well documented but still represented real concerns to the industry.

The third type was essentially similar to the second except that the incident occurred in the occupied cabin areas of the aircraft. Fire and smoke events in the cabin are typically less severe than those in hidden spaces because they are rapidly detected by the "human sensors," and they are accessible for suppression efforts. This raises the issue of whether a computer-based system for dealing with fires such as ACES should even include consideration of fire or smoke events which occur in the open, occupied spaces of an aircraft. The best way to make this judgment seemed to be to include them in one or more scenarios for assessment in the study process.

The problem analysis led most directly to the enumeration of many possible scenarios and the development of 13 specific ones used in the study. The scenario development process is described beginning on page 23. The use of of the problem descriptions was not, however, limited to the scenario development. The problem descriptions were also important in establishing the bounds of the sensor, the computer support and the cockpit interface analyses. These analyses are described below.

SENSOR ANALYSIS.

The basic concept of the ACES system is to provide assistance to the crew in detecting and managing in-flight fires. Inherent in this concept is the notion that the system would automate some or all of the sensing, information gathering and decision-making activities necessary to reduce the severity of in-flight fires. Thus, an analysis of the state-of-the-art of sensors for use in transport aircraft had to be undertaken to provide important feasibility information. Direct contacts with manufacturers of sensing devices and their literature were the primary sources of information for defining the role of sensors in an ACES system.

Early detection of the presence of a fire is an essential element in a fire safety system. From the moment of smoldering or flaming combustion, fire produces changes in the surrounding environment. In addition to thermal energy, solid and liquid particles and gases are introduced. With incipient fires, such changes can also occur well before actual smoldering or flaming. For the purposes of the following discussion, it will be helpful to define a few terms related to fire detection.

In 1974 the term "fire signature" was introduced to describe any product of a fire that changes the ambient conditions and is practical for detection purposes (Custer and Bright, 1974). At that time detection was limited to determination of the presence or absence of a fire. No information was generated that could discriminate between smoldering and flaming fires or between the slow buildup of cigarette smoke or condensed moisture and an actual fire. Present technology permits assessment of both the instantaneous level of the fire product and the rate of change of that product over time. Thus, the term signature as used in the concept of an ACES system will be expanded to include both the type of signature being sensed and its rate-of-change history.

To be useful, the change in the ambient conditions for a given signature must exceed the changes that could be due to non-fire conditions. Not all fire signatures are suitable for fire detection purposes. In an unheated aircraft cargo compartment, for example, temperature increases during descent might be interpreted as a possible fire. In a case such as this where a false-positive alarm can result in a major effect such as an emergency landing when there is no fire, sensor systems monitoring conditions associated with several different signatures are advisable. All other factors being equal, such as response time, weight and cost, the preferred signatures will be those that are most specific to the types of fire likely to be experienced and can generate the highest signal to noise ratio in the earliest period of fire development.

The term "sensor" as used in this report refers to the mechanism that responds to the presence of a given signature such as smoke or heat. A "detector" is the assembly that houses the sensor and any power supply or electronic circuitry associated with the sensor. If the circuitry to process the signal from the sensor, a device to sound the alarm and the power supply are all within this housing, the unit is a "single station" detector and can stand alone. Single station devices are also available that can permit remote sounding of the audible alarm. If only the sensor and signal processing circuits are present, the device is a "multiple station" detector and requires a remote alarm panel, power supply and other equipment. A multiple-station device, then, is part of a fire detection "system."

Detectors are generally categorized by the signature being sensed (i.e., heat, smoke, etc.) and by the installation geometry. Detectors classified by installation geometry may be of the spot-type that sense the conditions at a specific location in a compartment or space or of the line-type where conditions over an area or along the line can be monitored. Where air handling systems are present, it is possible to monitor conditions in a "volume" by placing a spot-type detector in a heating, ventilating or air conditioning (HVAC) exhaust duct. In large volumes or with large air flow rates, sensing of fire signatures may be delayed due to dilution effects.

Regardless of the signature being sensed, most detectors in use today respond in a binary, i.e., fire/no-fire mode. This limits the amount of information which the sensing subsystem can provide to the decision-making part of an ACES system. In a binary mode, a threshold level must be set. No alarm is sounded if the sensed level is below that threshold. If the threshold is set too high, fire and smoke incidents are allowed to develop to significant levels before an alarm is sounded. If the threshold is set too low, excessive false alarms are possible.

In order to overcome the limitations of a binary detector, it is useful as part of the ACES concept to consider continuous or analog signals as output from the detector. The technology for analog fire signature sensors exists today and will be discussed with individual fire signatures and sensor mechanisms below.

AEROSOL SIGNATURES. Beginning with the preignition phase of a fire, large numbers of solid and liquid particles are introduced into the atmosphere. During the preignition phase, the particles are of submicron size (5×10^{-4} to 1×10^{-3} micrometers) and are produced at temperatures well below ignition. Since particles below 10^{-11} micrometers do not scatter visible light efficiently, they are referred to as invisible aerosols. As the ignition temperature of a

material is reached, the concentration of invisible aerosols increases to the point where larger particles are produced by coagulation (Rodebush, 1950). As the process continues, small particles disappear by coagulation or evaporation, the large particles fall out of suspension and the remaining stable aerosol will have a size distribution between 0.1 and 1.0 micrometers. Both invisible and visible particles will be present.

Aerosol size distribution is related to whether the combustion process is smoldering or flaming (Bukowski and Mulholland, 1978 and Schiedweiler, 1968). In general, smoldering fires produce large particles (greater than 0.3 micrometers) and flaming fires small ones (less than 0.3 micrometers). For both fire types, however, the maximum particle population is in the 0.3 micrometer and below range.

The presence of aerosols can be sensed by several means, including the use of ionization chambers and light scattering or attenuation devices. The environmental effect of fire measured by ionization sensors is the change in conductivity of ionized air with increasing smoke concentration. The ionization sensor consists of an ionized air space between two plates, one charged positively and the other charged negatively. The ionization energy is provided by a small alpha or beta radiation source, usually Americium 241, directing energy between the plates. In the standby condition (no "smoke"), a small current (10^{-11} amps) flows across the chamber and is the baseline signal.

When aerosol enters the chamber, the mobility of the ions is reduced and the current flow through the chamber decreases. In most aerosol or "smoke" detectors, a predetermined change in the baseline current flow through the sensor is established as an alarm threshold. When the threshold is reached, a normally open circuit is closed and the alarm is transmitted. This type of operation of the detector would be a binary, i.e., fire/no-fire mode.

In order to represent fully a fire signature as defined above, the actual continuous output signal from an ionization detector must be available so that the rate of change of the signal can be assessed. A detector providing this feature would be operating in an analog mode. Since the ionization chamber produces a continuous change in current that is proportional to the concentration of aerosol present, all that is needed is circuitry that will process the sensor output so that the rate of change, as well as the instantaneous value, can be determined over time either at the detector or at a remote location. Analog ionization chamber detectors are available commercially for use in building fire detection systems. They will be discussed later in this report.

Ionization chamber detectors are considered spot devices and are generally installed at regular intervals on ceilings or on walls close to the ceiling. In small confined spaces, a single detector is often adequate. HVAC exhaust duct installations are also employed.

Fire aerosols will affect the propagation of light passing through the air. A beam of light of a given intensity in clear air, for example, will be attenuated exponentially as a function of the length of the beam, the concentration of particles and their optical properties. When the signal is attenuated to a predetermined level, the alarm is sounded. The light source may be a laser or incandescent bulb. A variety of photo sensors such as cadmium sulfide cells are used as receivers. These detectors are called projected beam detectors and

are generally used to supervise large open spaces. Projected beam detectors are line-type devices. In order for these systems to function, a clear line-of-sight path must be maintained. This requirement would make beam detectors unsuitable for most ACES applications.

The presence of particles also scatters light, a process that is clearly demonstrated by the "shaft" of light created by a slide projector in a room in which people are smoking. The scattering efficiency is related to the wave length of the light and the size of the particles (Bukowski and Mulholland, 1978). The nearer the particle diameter is to the wavelength of the incident light, the more light energy is scattered. Light in the ultraviolet range, such as from a xenon discharge tube, will scatter far better from particles smaller than 0.1 micrometer (those related to flaming and rapidly growing fires) than particles approaching 1.0 micrometer (those associated with smoldering fires). Infrared energy has wavelengths on the order of 0.4 to 4 micrometers and scatters more efficiently from these larger particles.

The scattering sensor uses a light source and a photo sensor receiver arranged so that no light from the source is seen by the receiver. Light sources are usually red or infrared light emitting diodes (LED). The more sensitive light scattering sensors use xenon sources. This source has significant energy in the ultraviolet, thus making it particularly sensitive to the small particles generated early in the fire. In the presence of smoke aerosol, light is scattered into the receiver. The receivers are commonly silicon cells. The receiver provides a continuous analog output of the change in smoke concentration, and, when a predetermined level is reached, the alarm sounds. Thus, in its typical installation, the scattering sensor operates in a binary mode. The scattering sensor is the type most commonly found in the cargo holds on commercial aircraft today. Because of its propensity to be "tricked" by any nonfire aerosol which will scatter light, it is generally installed in batteries of two sensors connected by an "AND" gate.

ENERGY RELEASE SIGNATURES. Throughout its course, a fire is continuously releasing energy into the environment. The rate at which the energy is released changes with time, producing several useful fire signatures. The energy release signatures can be further subdivided on the basis of the mode of heat transfer involved: radiation or convection.

Radiated energy signatures are found in the ultraviolet and infrared ranges of the energy spectrum and are characterized by discrete sets of spectral peaks and oscillatory frequencies that are associated with flames. Strong infrared emissions from burning hydrocarbons (plastics, liquid fuels etc.), for example, are found in the 4.4 micrometer region due to the presence of CO_2 and in the 2.7 micrometer region due to water vapor. Another infrared signature is a characteristic "flicker frequency" on the order of 5 to 15 hertz. Combining sensors for all three of the above signatures in one detector or detection system reduces the likelihood of false alarms. The sensors used are photosensitive cells, either doped or filtered to screen out all radiation but the infrared signatures. Ultraviolet signatures for flames exist in the 0.27 to 0.29 micrometer range due to the presence of CO, CO_2 and OH radicals. Detectors using radiated energy signatures are employed in aircraft engine fire detection systems. Radiant energy detectors can be considered to supervise a volume in that a flame will be sensed anywhere in the volume given that it can be "seen."

Convected energy signatures are related to increases in air temperature due to the fire. Like smoke, the signature is represented by the time/rate-of-change history of the sensor output. Smoldering or slowly developing fires will have low heat output and temperatures will rise slowly. Once flaming develops, fires tend to grow exponentially as a function of time. Typical flaming fires such as burning furniture grow at a rate equivalent to the square of time. A flammable liquid fire may have an exponent of four (see Figure 1). The actual rate of development of the various fire signatures will depend on the configuration of the fuel, the geometry of the compartment and the ventilation.

Sensors for convected energy signatures rely largely on physical, electrical or chemical changes caused by to generate a signal. These sensors operate in both binary and analog modes and can be of either spot or line-type. The binary devices use the mechanical energy of expanding metals or gases or the melting of a eutectic material to open or close a contact initiating an alarm. The expansion of air against a flexible diaphragm, for example, is used to operate contacts in line-type pneumatic tube systems and in spot-type devices. Binary heat detectors will initiate an alarm when a specified rate of temperature rise is reached or at a specified fixed temperature. Temperature settings are typically available between 135°F and 500°F.

Some convected energy sensors produce a continuous output which is the analog of temperature. Thermocouples, thermopiles, and thermistors are spot-type devices producing either a millivolt signal or a change in resistance as a function of temperature.

Continuous wire heat sensors consist of a tube containing a coaxial center conductor. Surrounding the center conductor and filling the outer tube or sheath, is a material that reacts to heat by changing the resistance or the capacitance between the center conductor and the sheath. A variety of different materials are used for each of the elements in these devices. Continuous wire heat detectors, although generally used with binary mode control units, often have sensors that produce a continuous analog of temperature. One unique line-type detector uses an optical fiber sensor that progressively attenuates a light signal passing through it in response to increasing temperature.

MISCELLANEOUS SIGNATURES. Fire produces a large number of chemical species such as water, carbon monoxide, hydrogen chloride and hydrogen cyanide among many others. Except for very special industrial applications, the fire gas signatures are not used routinely for detection.

AVIATION INDUSTRY FIRE SENSORS. In the process of examining the generic types of sensors available for use in an ACES system, several manufacturers were contacted and supplied information. It was not the intent of this study to conduct a survey of all available sensors. However, the information collected on specific products is believed to be highly illustrative of existing technology which could be applied to an ACES design. Therefore, it was decided to include herein a sampling of specific product references as a demonstration of the extent to which an ACES could be designed with "off the shelf" sensors. The fact that a particular product or manufacturer is or is not mentioned should not be construed as an endorsement (or lack thereof) of that product/manufacturer by the project or the FAA. The sensors discussed below are already in use by the aviation industry and meet the appropriate FAA and Military specifications. They are a representative sample of available devices.

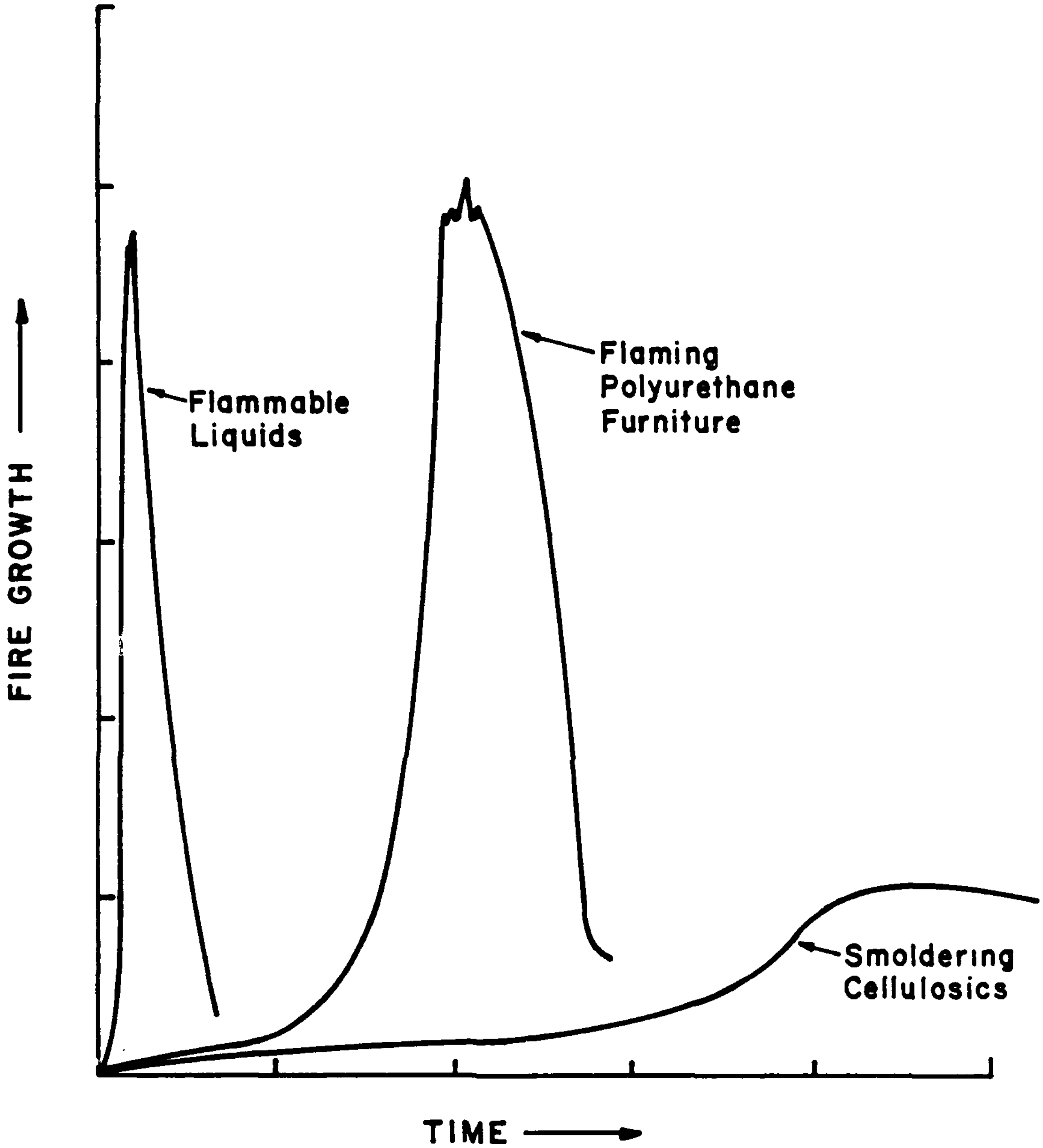

FIGURE 1. EXAMPLES OF FIRE GROWTH RATES

Heat Sensors. Aviation heat sensors are available in both spot and line configurations. Products by three companies were reviewed, Graviner (UK), ARMTEC (USA) and Fenwal (USA).

All three manufacturers produce line-type or continuous wire sensors. The Fenwal device uses a eutectic salt as the heat sensitive element in a coaxial configuration. As the salt approaches its melting point, the impedance drops suddenly allowing current to flow. Since the melting point is actually the "set point" of the sensor, this is considered a binary device.

The line-type sensors made by Graviner and ARMTEC react continuously to changes in the ambient temperature. The Graviner sensor responds with changes in both the resistance and the capacitance of the circuit containing the sensor. As temperature increases, resistance decreases and capacitance increases. In present applications, when the resistance and capacitance both reach predetermined levels, an alarm is sounded. Although the alarm function is binary in nature for the detector, the sensor itself is analog.

The ARMTEC line-type detector also uses an analog sensor. Here, the heat responsive element is a metal oxide semiconductor (MOS) that changes resistance inversely with temperature. As in the case of the Graviner detector, the sensor output is used to activate a binary signal to an alarm system.

Fenwal produces two spot-type detectors. One operates in a binary mode when a pair of contacts is closed by the forces created by differentially expanding metals. The other uses a thermistor as the sensor. A thermistor is a solid state temperature measuring device. As in the line sensors discussed above, the thermistor continuously changes resistance inversely with temperature and thus is an analog device.

Smoke Sensors. The aviation smoke detectors on the market operate on the same principles as most commercial devices using either photoelectric or ionization type sensors. Although an analog signal is produced by both sensors, the available detectors produce either a binary output or a two level alarm. Aviation smoke detectors are available for both ceiling mounting and HVAC duct operation.

The sensor in a photoelectric detector produced by Fenwal uses the light scattered from a red light emitting diode into a silicon photosensor to monitor the levels of smoke present. The detector has two levels of binary output: "pulsing" as a pre-alarm (low level of smoke); and, "steady" as the alarm mode (threshold level of smoke). It is possible that the circuitry built into the detector could be redesigned to produce an analog output as has been done with the commercial detectors discussed below.

COMMERCIAL SENSORS. Commercial sensors and detectors differ from aviation devices primarily in that they are not generally designed and tested to withstand the rigors of flight. Given the need, it appears technically feasible to upgrade suitable commercial detectors to meet the necessary FAA or industry standards.

Heat Sensors. A number of commercial heat detectors with analog sensors or output are available for both spot and line applications. The sensors operate on the same principles as the aviation devices above. Since devices

already exist that meet FAA and Military Requirements, no extensive review of commercial heat detectors was undertaken. A recently introduced optical fiber heat sensor does, however, warrant discussion as a possible ACES sensor candidate.

Produced by Systecon, Inc., the sensor is a fiber optic loop with an LED light source at one end and a photosensor at the other end. The fiber conductor has optical properties such that exposure to heat reduces the light transmission characteristics. In the present configuration of the detector, the output from the optical sensor is monitored and when the light level at the photosensor is reduced to 35 percent, a trouble signal (binary) is triggered. When the level of attenuation reaches 50 percent, a fire signal (binary) is sent. Although the detection system is not analog, the sensor is.

Smoke Sensors. Aerosol sensors used in smoke detectors all produce continuous analog outputs. Like heat detectors with analog sensors, smoke detectors employ an electronic circuit designed to respond at a predetermined sensor output level to generate binary alarm conditions. Some smoke detectors provide a continuous analog output. Photoelectric and ionization devices are available with alarm systems from a number of sources including Autocall (US), Apollo (UK) and Nittan (UK/Japan). Rather than use the term "detector" for these devices, they are called "fire monitors," "smoke/heat sensors," "analog sensors" or "analog detectors." These are all spot-type devices.

When a fire is in its earliest stages, very little heat is produced, and the smoke aerosols are transported largely by the movement of ambient air. When there is little air movement or if extremely early notification of a possible fire in a critical area is desired, submicron particle counting detection systems are available that periodically sample the air in the area protected. The samples are drawn to a sensing chamber where the level of aerosol present is measured and an analog output is produced. The two units available operate on different principles, but both respond to submicron sized particles, the earliest detectable fire signature.

One detection system produced by Environment-One draws the sample into a chamber containing air at 100 percent relative humidity. By lowering the pressure in the chamber, water condenses on the submicron particles allowing them to scatter light in proportion to the number of particles present. The present configuration has a slow sampling rate of four zones a minute. Usually a zone is a separate compartment. Each zone is analyzed once each second for the sampling period. While not a continuous analog output, the sampling rate could be increased by having more than one zone in a compartment. Four zones per compartment or continuous sampling of a single zone could make this device fully analog.

The Vesda detector by Fenwal uses the very short wavelength light (ultraviolet) from a xenon lamp to achieve scattering from the submicron aerosols. This is also a sampling system but uses a separate sensor for each zone. Each zone then is monitored continuously by the xenon lamp sensor and an analog output is provided.

One consideration with sampling detectors is the transit time when there are long runs of tubing from the sampling head to the sensor. This delay is to some extent compensated for by the extreme sensitivity of both of the devices described above.

"INTELLIGENT" ALARM SYSTEMS. Given that analog sensors are available for heat and smoke, an "intelligent" alarm system is possible. In this context, "intelligence" connotes the ability to exercise decision-making and employ adaptive threshold criteria. With an intelligent system, a number of algorithms for alarm levels can be developed ranging from a simple two level approach to a complex decision-making model based on such variables as sensor signal history, rate of increase of signal and forecasted time to critical heat or smoke conditions. An intelligent alarm system using current technology might also employ a capability to address and poll each heat and smoke sensor, record its signal level as a data point and use the data in an alarm algorithm. In addition, sensors could be monitored for contamination and operational status.

A review of the literature reveals the existence of a number of alarm systems that employ analog sensors and some level of alarm logic. In an April 1985 article in Fire Surveyor, eleven such systems available in England were reviewed. Three systems were described that meet all the requirements for "intelligence" and might be considered analogous to an ACES system for aircraft. They were made by Chubb (UK), Nittan (UK/Japan) and Hakuto (UK/Japan). The Chubb system supplies a standard serial computer output through an RS-232 interface and can provide emergency instructions by voice or visual display units.

Autocall (US) provides analog smoke detectors and employs fire algorithms in its AutoPlex system. This system is of particular interest because it uses more than one sensor mode and is intelligent. Although the present AutoPlex uses binary heat sensors, company representatives indicate no problems in providing analog heat capability.

Figures 2 and 3 show algorithms of smoke development and alarm logic suggested by Hakuto and by Autocall in their corporate literature. Figure 2 shows smoke level on the y axis and polling periods on the x axis. The horizontal line denotes a fixed threshold for alarm. The three curves represent three different types of fire in terms of smoke development. One shows rapid, intense development, one a gradual persistent development and the third is in between these two. The "fire decisions" are the points at which an alarm would be generated. Two of the curves show a reduction in smoke development leading to a "no fire" decision. Figure 3 is very similar to Figure 2: essentially the same three types of fire are depicted. The alarm logic is depicted by the symbol aligned with the appropriate number of sampling periods. These algorithms are examples only. Representative aircraft fire algorithms would be developed for the ACES system. The examples shown here are illustrative of the logic which can be employed in an intelligent system.

Based on a review of the analog fire sensing technology available today and the current state of the art in intelligent alarm processing equipment, it is feasible to conceive of developing an ACES using existing hardware. Development could likely be undertaken with either a minimal modification of existing aircraft fire sensors or by upgrading current commercial analog smoke sensors to meet FAA and industry standards. In addition, the ACES would require the development of appropriate alarm algorithms that are specific to in-flight fire scenarios. These would then have to be implemented in software on an appropriate processor in order to render the system intelligent.

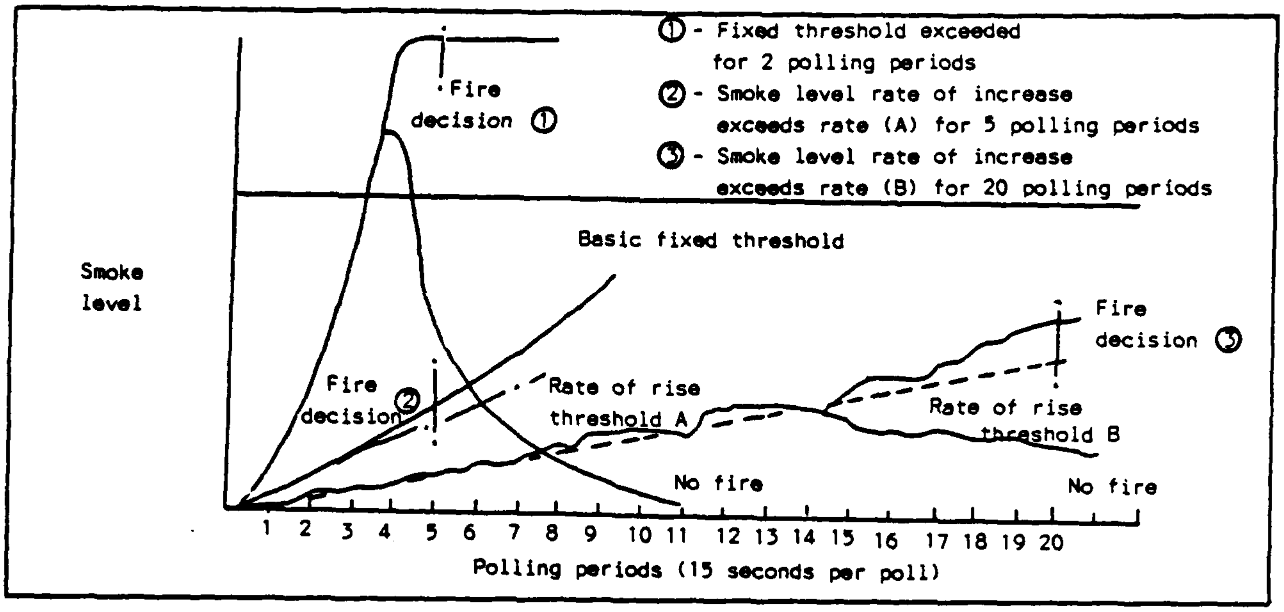

FIGURE 2. HAKUTO SYSTEM FIRE ALGORITHM EXAMPLES

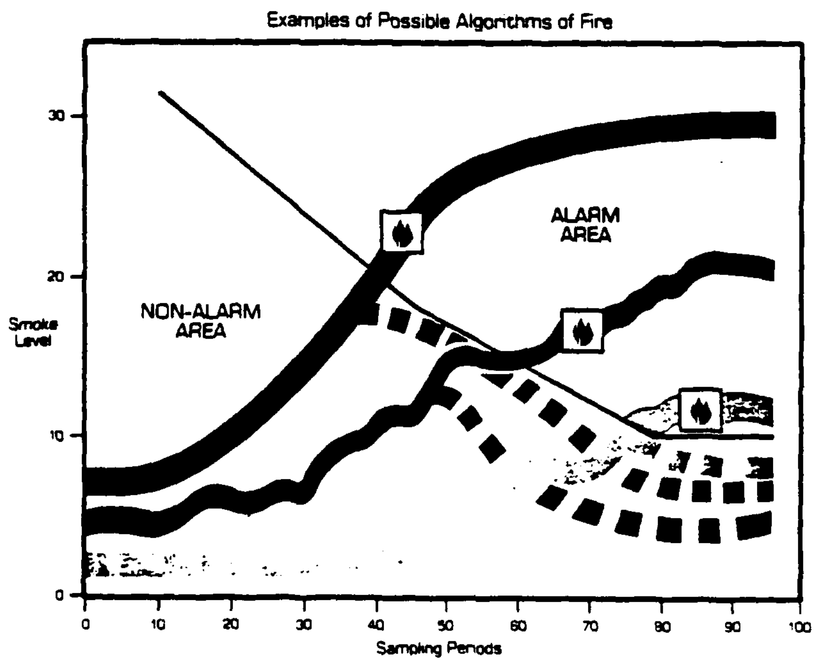

FIGURE 3. AUTOCALL/AUTOPLEX FIRE ALGORITHM EXAMPLES

COMPUTER PROCESSING ANALYSIS.

The basic ACES concept to be assessed assumed that the system would have an inherent degree of intelligence beyond that attainable with a conventional sensing system. This intelligence would allow the ACES to adapt its criteria to differing flight missions in order to achieve an overall system goal of maximizing correct fire/smoke incident detections and minimizing false alarms.

The need for remote sensors and the desire to minimize crew workload led to the decision that the ACES system would be computer-aided. The type of adaptive logic to be applied suggested that a fully developed ACES would operate as an expert system. In this study, however, no attempt was made to develop and assess a classical expert system. Rather, the goal was to determine if the expertise of an aircraft fire safety specialist could be captured and emulated in software and applied in flight. As will be seen from the definition of the hypothetical ACES later in this report, the system as formulated does, however, have many of the characteristics of a true expert system.

In light of the need to support ACES software on board a commercial transport, study efforts were devoted to an analysis of available or attainable computer hardware and software support. The present day jet aircraft has numerous dedicated processors which are designed to perform one or, at most, a few tasks. The Flight Warning Computer (FWC) and the Flight Management Computer (FMC) are two examples of major processors found on aircraft such as the Airbus Industrie A310. The FWC collects aircraft system data and generates appropriate warning stimuli when needed. The FMS manages the navigation of the aircraft according to a programmed flight plan.

Initial efforts were devoted to determining the feasibility of having the ACES system share an existing processor. Using an existing processor would minimize the cost of new hardware for the ACES. It would, however, generally increase software complexity and certification problems. Specifying a new, dedicated ACES processor would simplify development but would require additional hardware expense and engineering to find space to house the unit.

In the process of examining the existing situation, future plans were examined. This uncovered a trend in the aircraft industry away from the dedicated processor and towards an integrated avionics concept. The standards for this concept are being developed by the Airlines Electronic Engineering Committee (AEEC) of Aeronautical Radio, Inc. (ARINC). ARINC is a corporation whose stockholders include the major U.S. scheduled airlines, foreign flag carriers and various air transport companies and suppliers. Through the AEEC, ARINC formulates standards for electronic equipment and systems for the airlines. These standards are used to inform suppliers of the considered opinions of the airline industry.

The integrated avionics concept, which is already being adapted to the next generation of aircraft, involves using a number of multi-purpose host processors physically distributed around the aircraft to run programs which will address the majority of avionics needs. Each processing unit would address multiple functions. Extremely high reliability would be achieved by using fault tolerant 32 bit processors, executive software, built-in test equipment (BITE) and standard input/output interfaces. As appropriate, the programs for a

particular function, e.g., flaps and slats control, could be run in parallel on two of the processors for additional reliability.

Under the integrated approach, specific functions are accomplished by preparing implementing software in a common language. The present AEEC thinking calls for the preparation of that software in the Ada language. Ada was developed by the U.S. Government, Department of Defense, which now requires its use for all software in new weapons systems (Aviation Week & Space Technology, March 28, 1988).

Ada has been used to implement avionics systems on a variety of aircraft including the Northrop F-20 fighter and the Beech Starship. Developmental problems with early Ada compilers have largely been solved. Therefore, Ada is considered a good choice for future avionics development because the code is simple to maintain and modules can be easily reused for new applications.

Once the integrated concept is implemented, most of the existing dedicated processors will be replaced by compiled programs running on common processors and managed by an executive routine. For example, the FMC would be coded in Ada software, compiled and run on several of the processors. Input data for the programs would be obtained from a digital data bus which would also receive outputs which had to be passed from one program to another.

A complete description of the integrated avionics concept is beyond the scope of this report. Moreover, it is presently only a proposed design which will evolve extensively before it is used in a commercial transport. Its significance in the context of an ACES system is that future transports will already possess the supporting hardware needed to implement an ACES. In essence, the ACES logic would function as a program on one or more of the processors. This program would receive inputs from sensors appropriately deployed around the fuselage. The sensor output could either be wired directly to the ACES processor or converted to a digital signal at the nearest computer and distributed to the ACES processor on the data bus.

The industry trend to the integrated avionics concept provides a clear path to support ACES on future aircraft. Current design thinking among AEEC members is that there will be considerable spare processing capacity in the host computers. Therefore, ACES can be readily accommodated. The hardware and software computing needs of an ACES system as envisioned in this study will have to be met by an Ada program if the system is to be integrated into future aircraft.

HUMAN FACTORS AND CREW WORKLOAD ANALYSIS. ACES must function as a human-machine system. As such, it is not necessarily intended to replace crew functions, but, rather, to support them by providing accurate, reliable information in a timely, easily assimilated way. The problem analysis suggested that the crew needed assistance in several areas including receiving and interpreting warnings, retrieving checklist information and following procedures. In addition, the ACES would, by definition, interact with the crew during times of high stress and workload after a fire had been detected. Therefore, the ACES should be designed to reduce the additional workload inherent in responding to the emergency as much as is consistent with an effective allocation of functions between the crew and automated systems.

In order to determine the crew interface needs of an ACES system, analyses of existing and contemplated warning and crew response systems were undertaken. These were accomplished by a literature review, referencing the flight crew operating manuals of the airlines and airframe manufacturers, discussions with pilots and human factors specialists and direct observation in the cockpits of existing aircraft.

The modern aircraft cockpit contains an abundance of alerts and warnings intended to direct the attention of the crew to information which is important to the safe and/or efficient progress of the flight. In most newer aircraft, these alerts and warnings are handled by one or more flight warning computers (FWCs) which collect status information from sensors, apply appropriate decision rules and activate the specified alert or warning signal.

Overall, the vast majority of cockpit alerts and warnings are presented to the crew through auditory and/or visual modalities. The one common tactile warning, the stick shaker which signals an approach to a stall, will disappear as more aircraft adopt sidestick fly-by-wire control systems with inherent stall protection.

The current presentation of warnings and the contemplated approach for the next generation of aircraft follows the master warning concept. Under this concept, the existence and degree of problem is indicated through an auditory signal, and the specific nature of the problem is presented visually. In older aircraft, the pilots must often scan a variety of instruments and indicators throughout the cockpit to localize the cause of the warning. The current and contemplated generations of cockpit design employ electronic centralized monitoring cathode ray tube (CRT) displays to reduce the amount of visual scanning required to localize a fault. The Airbus Industrie Electronic Centralized Aircraft Monitor (ECAM) system on the A310, A300-600 and A320 and the Boeing Engine Indication and Crew Alerting System (EICAS) on the 767, 757 and 747-400 are examples of the centralized monitoring concept. Both of these systems employ computers to monitor the information from sensors throughout the aircraft and to establish the various alert or warning conditions.

In addition to assisting the pilots in localizing the reason for a warning or alert, centralized monitoring systems also provide some alerts and warnings directly without associated auditory alerting signals. The problems highlighted in this manner are typically less critical than those which are coupled with an auditory warning. An example would be brake temperatures which are high but not critical. The use of color CRT displays in the centralized systems makes it possible to indicate alerts through a change of color. The typical paradigm is to show values within the normal range in green, those approaching a critical value or trending towards out of range levels in amber and actual out of range values in red. In order to provide a rapid differentiation between warning and system status messages, the ECAM and EICAS under normal operations dedicate one CRT as a warning display and the other as a system display.

The actual alert or warning presentation is a function of the criticality of the situation, the response time requirements imposed on the pilots and the number of correct response modalities. Minor alerts, such as the loss of a redundant system, are typically displayed by amber warning lights or a message on the warning display CRT. Moderate alerts, such as the cockpit intercom or the altitude alert which indicates that the aircraft is nearing a preset altitude after

climb, are usually signalled by a single chime. In the case of the altitude alert, this chime is typically coupled with a signal light on the control panel. For all minor alerts, however, the chime tone is relatively mild compared with other cockpit warnings.

Alerts and warnings of the most serious nature are usually signalled by a more insistent chime or horn sound, such as a continuous repetitive chime for an engine fire or a "cavalry charge" for an autopilot failure, and confirmed by a visual display.

Some alerts and warnings are not readily adaptable to the master warning concept. For example, when the available response time for the crew is extremely limited or the crew's attention must be focused on a particular instrument or out of the windscreen, there is not sufficient time for scanning the cockpit or centralized monitor and reaching a decision. These critical alerts and warnings are therefore presented using a voice synthesizer. The message can be an immediate command to action as in the "PULL UP" call from the ground proximity warning system (GPWS). It can also be a critical advisory such as the "GEAR IS UP" message when the aircraft enters a final approach configuration and the landing gear has not been deployed.

Advances in synthetic voice technology have permitted its use as a routine alert. In particular, synthetic voice alerts are beginning to see widespread use in new cockpits (e.g., the A310) to replace routine information calls from the nonflying pilot to the flying pilot. These include calling the radio altitude on final approach, indicating the acquisition of the glide slope and noting passage of the aircraft over the approach markers. The automation of these routine alerts frees the nonflying pilot for other cockpit duties including "heads up" views from the aircraft to check for traffic.

In general, the modern cockpit has sufficient warning capability to accommodate additional ACES-related indications. The critical design issue is to select a warning modality and specific warning format which are consistent with existing practice, the ACES mission and the likely scenarios under which an ACES system will come into operation.

The latest warning systems, such as the Airbus Industrie second generation ECAM in the A320, go beyond issuing a warning and identifying the fault. They also present the corrective checklist and a synoptic view of the failed system. For example, when cargo compartment smoke is detected by the sensors on the Airbus A310-300, a continuous rapid chime is sounded. At the same time, the identification of the problem and the corrective checklist appear on the warning display (left CRT). The system display (right CRT) shows a schematic of the air conditioning system indicating the positions of the air flow valves for the involved compartment (they close automatically) and the measured compartment temperatures.

Further extensions of the current warning concepts have been examined by Boucek et. al. (1985). In addition to a separate alerting display, they also evaluated various means by which the pilot could accomplish the displayed checklist items including voice and touch control, multifunction keyboards and automatic systems. They concluded that the choice of control system affected the performance of the entire flight status monitoring system. They also indicated that the pilots they used as subjects preferred automated approaches

but were concerned about the reliability of systems which would bypass their decision-making and apply countermeasures.

Discussions with airline and industry personnel in this study suggested that the ACES warning subsystem should operate in much the same fashion as those on the latest generation of aircraft. They also expressed concern with the reliability of fully automated systems. Moreover, in the context of an ACES for in-flight fires, they saw little benefit to automating the application of countermeasures. There was, however, a strong sentiment that a system which executed the checklist items at the pilot's command would be beneficial. This approach eliminates the need for the crew to locate the appropriate control for a particular action. It could also be implemented in combination with an "audit" system which would verify that all of the checklist items had been performed and warn the crew if an item had been omitted.

The results of the human factors and crew workload analysis indicated that radical departures from the current approach were generally not warranted nor were they acceptable to flight crews. Thus, the ACES interface with the crew could best be modeled after the current generation of high automation aircraft.

SCENARIO DEVELOPMENT.

The preceding parts of this Section have described four distinct analyses which produced information and guidance for the definition of the ACES concept. They also produced data required to develop the scenarios. The process of scenario development is described below.

SOURCES. This technology assessment was concerned primarily with the in-flight fire threat (other than engine, and lifting and control surfaces) as it exists in today's air transport system. While this threat may change in the future with changes in aircraft size and configuration, varying route structures and other system characteristics, the focus was on today's threat. If an ACES technology can be shown to cope effectively with today's threat, it is reasonably likely that the technology can be adapted to meet future variations. Thus, the in-flight fire scenarios developed for this study were selected to be representative of today's problem. The most significant sources for such scenarios were the reports of actual in-flight fire or smoke events made by NTSB, FAA and the airlines themselves. One earlier research report on aircraft ventilation (Lorengo and Porter, 1986) contained fire and smoke scenarios that were also useful in this study.

The study staff, using input from FAA as well as from airline personnel and their own knowledge of air transport and fire development, created scenarios which are realistic and plausible and encompass a variety of outcomes. The scenarios include false alarms as well as totally catastrophic fires. Also, the crew responses range from poorly handled tragedies to models of appropriate, fully correct emergency procedures. The set cannot, of course, be claimed to be exhaustively complete. It is, however, broadly representative of the in-flight events that have recently occurred and could be experienced today.

In all, 13 scenarios were developed and used in this study; each of these was developed in a way that shielded actual events from identification. Aircraft types were not identified and no corporate or individual names were used. There are four scenarios adapted directly from actual events. These describe

the events, the procedures followed by the crew and all other details exactly as contained in the investigative reports. These scenarios are presented in different settings to make them anonymous. The extensive investigations which surrounded these four events provided a rich source of scenario data which was considered to be extremely valuable to these analyses.

The remaining nine scenarios depict situations derived from actual events or from concerns of industry personnel contacted during the study. Because these incidents typically had less catastrophic outcomes than the first four, there were no detailed investigations. Therefore, the event sequences for these scenarios were developed based on the type of aircraft and the flight characteristics postulated. The crew procedures in these scenarios were written to be consistent with the aircraft type and with the nature of the event. Some plausible errors were introduced to broaden the basis of evaluation of both the ACES and the non-ACES systems. The particular situations were selected to illustrate potential fire or smoke incidents not addressed in the other scenarios.

SCENARIO APPLICATION. In the conceptualization and in the implementation of this study, the fire scenarios were the vehicle by which the assessment and evaluation tasks were performed. Scenario development began with the preparation of a generic outline of scenario content. The outline was designed to capture sufficient detail of the incident and of the crew response and to allow a valid assessment of the ACES concept. This was followed by the enumeration of candidate scenarios from which a final list of 13 fire/smoke incidents was compiled. Even though the study contract stipulated that only 10 scenarios would be developed, it was concluded that the 13 incidents provided a more complete scope to the study. Thus, the first application of the scenarios was, in effect, to define the bounds of the study. Even before the contents of a single scenario had been written, the specified outline of a scenario description and the selected incidents established both the scope and depth of the study.

As the study progressed, the staff completed drafts of each of the scenarios which were used to facilitate discussions with FAA air transport and airframe manufacturing personnel. In this application, the scenarios were reviewed and refined, but, more importantly, they served to stimulate creative thinking about the concept of an ACES as well as about the potential technologies. The scenarios served as vehicles for testing, refining and revising possible ACES concepts and technologies. This was an iterative process in which all of the study participants took part.

At the end of this phase, the scenarios had evolved to a final form in which each incident and the crew's responses were realistically and completely defined. At this point in the study, the scenarios were used as a basis for describing a timeline sequence of events and responses in each incident and the effects of each event and response. This was done for the present fire detection warning and systems and the present response systems, i.e., a non-ACES system. A similar analysis was then performed applying the ACES concept. Using the results of these two analyses, a determination was made of the potential operational benefits and limitations and the methods of employment of an ACES system.

The scenario analyses were structured to reflect a simple, generic model of four processes considered to be common to dealing with any in-flight fire or smoke event: detection, localization, identification, and evaluation/action. Evaluation is further divided into risk assessment and countermeasures identification. Action includes countermeasure selection and implementation. The analysis of each scenario resulted in a record of the time required to complete each of the four processes and a qualitative assessment of each process. Finally, the opportunities, and possibly the means, for improving these processes were identified. A comparison of the analyses with and without an ACES system across all of the defined scenarios provides a direct assessment of the potential benefits of an ACES system.

A brief description of each process and its analysis follows in order to provide the reader with the context for interpreting the scenarios and their associated analyses.

Detection. Detection is the means by which the Flight Deck Crew becomes aware of each event as the incident develops. In present aircraft, fire and smoke detection can be by automatic means such as a thermal or a smoke detector or it can be accomplished by a human sensor such as a crew member or passenger. Under the ACES concept, automated detection is emphasized. Detection of other, circumstantial evidence which can be used to discriminate real fires from false alarms and accelerate the detection process are also considered. The major criteria for detection concern the time required as well as the quality of the information returned. Essentially this reduces to the speed and accuracy of detection.

Localization. Localization in the fire model has to do with determining the source of the fire or smoke. This determination of where the incident is located and of its fuel source are critical factors for the subsequent processes of Identification and Evaluation. The timeliness of localization relative to the rate of fire development and the accuracy of position determination and fuel source are the major analysis issues.

Identification. The identification process includes determination of whether the event is truly a fire/smoke event or is a false alarm as well as identification of the type of fire and the stage of fire development. Analysis relative to identification is concerned with how quickly and accurately the nature of the event is made known to the crew.

Evaluation/Action. In the generic model, this process has to do first with risk assessment: what is the danger to aircraft and to persons on board? The process then deals with countermeasures identification, selection and implementation. Countermeasures include fire suppression as well as control of crew and passengers and aircraft control and maneuvering. The analysis of this area is concerned with the timeliness of the evaluation as well as the appropriateness of countermeasure identification, selection and implementation. The ultimate criterion in this area is the extent to which the countermeasure produced a timely and safe resolution of the incident.

Each of the analytical steps just described played an important role in the outcome of this study. The information obtained was used throughout the effort as input to decision-making and for validity testing. The initial product of the integration of the findings was a description of the characteristics of an

ACES system which could be used to assess the feasibility of the concept. These characteristics are presented below.

AN ACES SYSTEM

The analyses showed clearly that the ACES system concept used for feasibility testing should be computer-based because of the required amount of processing and the need for rapid response. Further, remote sensing should be included because of the large amount of inaccessible volume in the fuselage which must be protected. Thus, for this analysis, ACES is conceptualized as a person-machine system consisting of hardware and software. This ACES system is, in turn, a subsystem of the total avionics suite on a commercial aircraft.

The hardware and software characteristics of the proposed ACES system configuration are presented below. The hardware is grouped into: Sensor, Data Input, Processor, and Control and Display. Every attempt has been made to insure that the concepts included here are realistic with respect to the state-of-the-art and in keeping with current and contemplated industry practices. It must be noted, however, that this was a technology assessment and not a design study. Thus, some of the ACES system characteristics described here may not be the most cost-effective way to achieve the desired functionality. Further, certain detailed system design features, such as the exact number and placement of sensors within an aircraft, remain to be determined.

HARDWARE.

The ACES system will include a battery of primary sensors, other data inputs, computer processing and a crew interface. Each of these aspects is described below.

SENSORS. The ACES system will employ "primary" sensors, i.e., sensors whose only function is to detect fire and smoke incidents. In order to specify the sensor requirements of the system, it is necessary to list the types of fire signatures to be used, the nature of the sensor outputs and the possible locations of sensors throughout the fuselage. Two signatures appear to be best suited for consideration in ACES, the invisible aerosol signature (particles less than 0.3 micrometers) and the convected energy signature.

The aerosol signature was selected because the small particles are produced in both smoldering and flaming fires and are generated early and in large quantities in rapidly growing fires, which are the ones with the most urgency. The best aerosol sensors for this purpose are spot devices using xenon light sources, ionization chambers or particle counters.

The convected energy signature was selected because, like smoke, fire gases and hot air rise and move throughout a space and tend to accumulate at the highest part of the monitored space where sensors can easily detect temperature changes. These temperature sensors are also desirable because they can detect the propagation of energy in adjacent spaces thereby providing an additional validity test for the presence of a fire.

Inherent in the proposed sensor deployment is the capability to combine information about multiple fire signatures for greater confidence in the alarm indications. A rapid increase in aerosol concentration with a decrease in air temperature is much less likely to denote a fire, for example, than is a rapid increase in both signatures.

The sensors specified for the ACES system must respond rapidly and predictably to changes in signature levels. The hardware must be physically robust and capable of meeting all applicable standards and specifications.

Analog outputs from the both aerosol ("smoke") and convected energy ("heat") sensors are required. Analog information is essential in order to achieve the degree of intelligence needed to overcome many of the problems inherent in the trade-off between rapid detection and high false alarm rates. The benefits of the analog sensor output can best be seen through a brief discussion of the relative quality of information from sensors with binary (fire/no-fire) outputs and those with analog (continuous data value) outputs. The following discussion will develop a set of fire or non-fire conditions that could be inferred from a given type of fire sensor signals or sensor conditions. It will be assumed that both heat and smoke sensors housed in a single unit will be present in the area being monitored.

Two approaches will be compared. The first will assume that the information is presented in a binary format, i.e., threshold heat/no heat or threshold smoke/no smoke. It is assumed that the alarm will actuate for each sensor when a predetermined, fixed aerosol concentration or air temperature threshold is reached, and that the threshold levels are consistent with current aviation practice. While the determination of the optimum thresholds is beyond the scope of the current effort, it is one of the most important and challenging tasks for a detailed design study.

The second approach will assume continuous monitoring of the instantaneous aerosol and heat levels. Because the sensor outputs will be analog, data about the rate of change of smoke and heat can be derived. In the analog system, it will be assumed that a maximum or "redline" smoke or heat condition can be defined that would indicate an automatic "emergency" sensor condition. For the purpose of this example, the redline conditions will be assumed to be fixed at the same value as current aviation smoke and heat detection thresholds. The discussion of software later in this Section will introduce the concept of variable thresholds as proposed for the ACES implementation.

Considering the first approach, there are four possible sensor conditions that can arise from combined binary format smoke and heat sensor systems. These are shown as a matrix one the following page. The cells are defined by the presence or absence of heat or smoke at a predetermined, fixed threshold level. As is customary in existing systems, these thresholds would likely be set quite high to avoid excessive false alarms. The cells for each sensor condition are numbered from one to four for reference in the following discussion.

In Condition 1, the presence of both aerosol and heat at threshold levels is indicated. In this condition, it is most likely that a fire exists which is producing both smoke and flame and is rapidly growing. At this point, the body of flame may be either small or large. If both the heat and smoke alarms

activate at the same time, conditions are likely to be worse than if there is a delay between the smoke and heat alarms.

	THRESHOLD HEAT	NO HEAT
THRESHOLD SMOKE	1	2
NO SMOKE	3	4

It is possible but highly unlikely that malfunction of the aircraft heating system controls combined with a particulate source such as overheated electrical insulation could produce the same sensor condition. If such a malfunction were to occur, it could not be differentiated from a real fire by this detection system.

Under Sensor Condition 2, there is threshold smoke with heat below threshold. A slowly developing smoldering fire or a fire developing in a closed or partially closed container could produce smoke aerosol without releasing sufficient heat to reach threshold and trigger an alarm. A fire may also be developing in an area where there are no sensors and the smoke has cooled to a temperature below the heat threshold and migrated into a monitored area. Overheated electrical insulation can also produce large volumes of aerosol at detectable levels without significantly heating the local environment. Depending on the nature of the electrical fault, a fire may or may not result. A non-fire possibility could result from rapid cooling of high humidity air resulting in condensation (fog) aerosol, a known source of false alarms in smoke sensors.

The presence of threshold heat without threshold smoke is indicated by Sensor Condition 3. It is difficult to imagine a real fire scenario that would lead to this sensor condition if the sensors are co-located unless the aerosol sensor is not functioning. While some fuels like alcohol and butane will burn with little aerosol production, this only occurs in the absence of other burning materials, an unlikely situation.

Sensor Condition 4 implies that neither aerosol nor heat are present at threshold levels and would normally be interpreted as a no-fire condition. If a fire were present, it would be producing aerosols and heat at levels that would not raise the ambient aerosol concentration or air temperature to the alarm threshold. Therefore, the sensor battery would provide no clues that a fire existed. These situations are characteristic of the early stages of a fire that will eventually trigger an alarm or an extremely small fire that never grows significantly.

In contrast to the above, the second sensor approach involves the use of analog sensor outputs interpreted by an intelligent program. Continual monitoring of analog outputs will provide the information needed to permit determination of the rate of change of both smoke aerosol concentration and air temperature. It

would permit measuring the levels of smoke and heat over time and to determine if they were trending upward (had a positive slope).

To illustrate this sensor approach, the added information it provides can be integrated into a matrix similar to the one used earlier. This second matrix contains nine cells lettered A through I and is shown below. The nine cells are derived from three conditions of each sensor. These are a redline or threshold level, an established positive slope or increasing condition and a "flat" output (no heat or no smoke change from ambient).

	REDLINE HEAT	INCREASING HEAT	NO HEAT
REDLINE SMOKE	A	B	C
INCREASING SMOKE	D	E	F
NO SMOKE	G	H	I

Condition A has both sensors at the redline level. This is functionally equivalent to Sensor Condition 1 described above for the binary sensor approach. It almost surely indicates that a serious fire is in progress with active flaming and smoke production.

In Sensor Condition B, smoke is at redline and heat, although not at redline, is increasing. If the rate of heat increase is slow, there may be either a smoldering fire in the compartment in question or a fire developing remotely with the smoke preceding the heat. If the heat is rising rapidly, it is likely that the fire is actively flaming and in the same compartment or area as the sensor unit.

Sensor Condition C would not likely represent a fire other than one of a smoldering nature. The aerosol that is present might be condensation or moisture, as discussed before, or possibly from leaks of refrigerants, hydraulic fluid under high pressure or a ruptured aerosol container. Under these conditions there would be no temperature rise expected. With the smoke at redline, however, there still would be cause for concern. If there were a real smoldering fire, the temperature would eventually begin to rise and Sensor Condition B would be reached. If the heat sensor data indicates that the temperature in the compartment has dropped below the dew point of air at the last airport, the conflict could be resolved negatively. If the condition changes from no-smoke to redline instantaneously with no heat, the indication is likely the result of a smoke sensor short rather than a real condition.

Sensor Condition D could indicate overheated equipment approaching the point of flame production or perhaps only reaching temperatures sufficient to char or scorch materials but not ignite them. Heat at the redline would suggest a serious cause for concern and would almost certainly dictate an emergency response.

Indications of both increasing smoke and heat as in Condition E, are a very strong evidence of fire. Flaming has most likely begun. If either sensor is indicating rapid rate of increase, the situation is likely quite critical. Even a relatively slow increase of both smoke and heat, however, would be an early indication of a serious problem.

Sensor Condition F would indicate either no fire or the very early stages of the smoldering fire associated with Sensor Condition C.

Sensor Condition G is not likely to be a fire and might best be considered an overheat warning. It is, nonetheless, a serious situation because of the extent of heat involved. A known malfunction of a heating system or other heat generating equipment would be an adequate explanation for the existence of this condition.

Increasing heat in the absence of smoke would not necessarily associate a fire with Sensor Condition H. This condition could indicate the early stages of equipment failure or perhaps the normal temperature rise associated with a descent.

Sensor Condition I would indicate a non-fire status. It would be the normal operating condition.

This comparison between a smoke/heat sensor battery with binary indications and one with continuously monitored analog outputs indicates clearly why the latter is preferred for an ACES application. The combination of smoke and heat sensors covers a wider range of fire conditions than either type alone. The continuous analog output when combined with an "intelligent" processor permits the examination and interpretation of trends. These in turn can speed the identification of real fires and help discriminate between real and false alarms.

Even though it is desirable to use ACES sensors in smoke/heat pairs, it is recognized that physical limitations in certain areas of the fuselage and economic constraints might preclude the universal adoption of this approach. In fact, without detailed cost-benefit and reliability/maintainability studies which were beyond the scope of the present effort, final decisions on the number and location of ACES sensors are not possible. This study did, however, examine candidate locations for sensors. In the discussion which follows, the relative frequency of occurrence of fire or smoke events in various aircraft areas is based on data provided by Starrett et al. (1976).

The type and number of sensors which are reasonable to use in a given aircraft functional area will depend upon the nature of the fire scenarios expected, the geometry and degree of compartmentalization of the area, the ventilation parameters and the flight criticality of the aircraft equipment exposed.

The following is a list of possible areas in which ACES fire sensors could possibly be installed. Also included is a brief description of the sensors which appear best suited to each area and the rationale for their selection. Some consideration is given to the ACES system role in the accessible cabin areas, however, a remote monitoring system is particularly suited to detection of incidents in inaccessible areas and the inclusion of other areas must be based on such factors as degree of risk and cost.

Galley Areas. Galley areas both above and below deck were the most frequent locations of fire/smoke incidents. Of 530 total incidents identified, 376 were in the pressurized area of the aircraft. Thirty-nine percent (148 incidents) of these took place in galleys (133 in upper galleys and 15 in lower lobe areas). Galley incidents are usually of low severity, but they often involve large amounts of smoke and require a diversion of the flight.

In order to monitor galley areas, a smoke/heat battery of sensors should be used. Additional heat sensors might be located in critical areas in or around appliances that are likely to overheat and cause a fire. This would provide an even faster response than could be obtained from monitoring the entire galley area.

Galleys are areas in which temperature and, particularly, smoke can be expected to vary more than is typical for other parts of an aircraft. Therefore, the interpretation of sensor outputs and the establishment of redlines for galley areas would have to be based on special criteria. Since above-deck galleys are usually open to the cabin and therefore capable of being sensed by passengers and crew, fire/smoke detectors could be thought to be unnecessary. Industry personnel contacted during this study stated the position that remote sensing in upper galley areas is not needed and would not be cost effective. This response may, however, stem from concern over the relatively high possibility of false alarms and their detrimental effect on system reliability based on current fire detection system performance.

Cabin. The cabin areas, both first class and coach combined, were the second most frequent location for fire incidents with 67 (18% of these in pressurized areas). Cabin areas are characterized by a wide range of electrical and electronic equipment ranging from fluorescent light ballasts to multiplexed entertainment systems. All of these are potential sources of smoke and fire. In addition, smoking by passengers can result in the ignition of cabin materials.

The open cabin areas represent an extremely large volume to monitor with smoke or heat sensors. Although temperature sensors are already present as part of the environmental control system, their response time to a fire event would almost certainly be longer than the time it would take a passenger or crew member to detect an incident. Given the presence of human sensors in the open cabin areas, benefits from remote sensing appear small. Nevertheless, the relatively high frequency of incidents in these areas suggests that the ACES design effort should examine cabin sensors. For the feasibility analyses in this study, however, it was assumed that open cabin areas were not remotely monitored.

Cockpit. The flight station/cockpit was the third most frequent location of fires within the pressurized area of the aircraft. Sixty-two incidents representing 16 percent of the total in pressurized areas were involved. Consideration of monitoring the cockpit area must contend with two opposing factors. Since all or most aircraft systems are routed through the cockpit, it is a highly concentrated locus of electronic equipment, much of which is concealed behind the instrument panel. In addition, the crew often uses smoking material and carries numerous combustibles and ignition sources such as air charts and cigarette lighters. These factors suggest the need to monitor the cockpit area.

On the other hand, one or more highly trained crew members is always present on the flight deck. Hence, an excellent "sensor" is already available, and there is no need for additional crew alerting once an incident is sensed.

Because of the extensive amount of electronics in concealed areas, smoke and heat sensors behind the instrument panel are worthy of consideration. Since much of the concealed space in question is cooled, sensors might be considered for inclusion in ducts. General area monitoring of the cockpit itself should also be examined in any detailed design study. However, it is not likely that cockpit open area sensors could be justified.

Auxiliary Power Unit. Auxiliary power units (APUs) are a frequent source of fire and smoke incidents. Together with other equipment, they were involved in 12 percent of the incidents. Depending on the specific aircraft design, the APU may be totally outside the pressurized area of the fuselage or divided between pressurized and non-pressurized areas.

The actual APU installation would dictate the type and number of ACES sensors which should be considered. For example, if the APU were contained in a small, concealed space, an approach similar to that taken in the cheek areas (see below) would be indicated in addition to the fire sensors already incorporated in the APU. It is also worth considering line-type heat sensors incorporated in the wiring harnesses leading through the pressure bulkhead. These would be able to detect overheating prior to ignition.

Air Conditioning Packs. Spot heat and smoke sensors placed in the discharge ducts from air conditioning units will detect unusual temperature or smoke arising from equipment failure. As with galley areas, air conditioning packs will likely require the development of unique alarm signatures because of the special failure modes they can experience. For example, as depicted in Scenario 9 of this study, air conditioning packs can generate large amounts of smoke in the absence of fire and with little heat production.

Lavatories. Lavatories are a major area of concern for several reasons. First, they have a relatively high experience of incidents (9% of the data), and they have been associated with tragic outcomes. Second, there have been many reports of smoking and the use of illegal substances involving flame production in the lavatory. Third, lavatories house combustible material including paper towels and amenities. These characteristics strongly suggest the use of both heat and smoke sensors. Ceiling-mounted smoke sensors would provide an early signal of a possible fire, as well as supplemental detection information. The heat sensor is also recommended to warn against opening the lavatory door under conditions of rapidly rising temperature.

If ACES sensing is extended beyond area monitoring, spot heat sensors in the confined spaces of the amenities cabinets and trash receptacles would provide "localizing" information when smoke is sensed in the lavatory. The relative benefits of monitoring trash bins instead of, or in addition to, the present practice of equipping them with automatic extinguishers is worthy of further investigation.

Avionics/Computer Bay. The avionics/computer bay, typically located beneath the cockpit, has been the location of about 2% of the fire and smoke incidents. The avionics bay is a densely packed area of electrical and

electronic equipment and usually contains the aircraft batteries. Since the avionics/computer bay contains critical electronic equipment, it should be considered for a smoke/heat battery of sensors. In addition, the benefits of very early warning provided by submicron particle sensors is worthy of consideration.

Present installations typically involve ceiling or exhaust duct installations. This approach can be coupled (as in the Airbus A310) with a "sniffer" fan which allows the crew to sample the duct air to detect the characteristic odor of burning insulation. Placing sensors in individual equipment cabinets should be assessed in the design of an ACES because they would provide localizing information. This might permit the crew to turn off only the equipment actually involved rather than having to engage in large-scale load shedding to stop smoke generation.

Cargo Compartments. Cargo compartments, while they are the location of only 2% of the incidents, are of great concern to a fire management system. They are essentially inaccessible during flight and thus require very reliable sensing and containment or suppression methods. Moreover, in spite of the best efforts of airlines and regulatory agencies, it is impossible to exercise complete control of what is placed in them. As a result, incidents in cargo compartments can become quite severe because the fire may have time to grow and spread before it is detected and the compartments may contain highly flammable material.

Cargo compartments are a prime candidate for the use of the dual smoke/heat battery of sensors primarily because of the many combustion sources. Depending on the volume of the particular cargo compartment to be monitored, more than one pair of smoke/heat sensors might be required. In addition to the heat sensors co-located with the smoke sensors, line-type devices could be mounted on the ceiling running the entire length of the compartment to speed detection and assist localization.

An alternative approach to be considered would be to monitor the entire volume of a cargo or baggage compartment with spot heat and smoke sensors in the air conditioning supply and exhaust ducts. By monitoring both the incoming and outgoing air, it can be determined whether or not the source of the heat or smoke is in a given compartment. A potential problem with this approach is that time may be lost as a result of dilution of fire signatures by the air conditioning system. If the cargo compartment vent ducts are not isolated, however, this information may be ambiguous.

Cheek, Attic and Other Fuselage Areas. A typical transport aircraft will have a relatively large volume of "trapped" space outside of the passenger cabin, cargo holds, cockpit and avionics bay. This volume is found above the cabin ceiling (the "attic") or between the cabin walls and the fuselage (the "sidewall") or between the cargo compartment walls and the fuselage (the "cheek"). Many of these areas are interconnected with respect to airflow, although the movement of air may be restricted due to fuselage ribs or fire stops.

Because these hidden areas often carry electrical and/or hydraulic lines and are subject to lint build-up, they should be considered for monitoring. The specific choice of monitors can only be made with reference to a particular

aircraft design. For example, the Boeing 747-400 as configured by most carriers will use part of the attic as a crew rest area. Since this area will not be continuously occupied, it is a good candidate for a smoke/heat sensor pair. Most cheek areas, on the other hand, have relatively small volumes. It may therefore be sufficient to monitor them with continuous filament, line-type heat sensors.

The presence of long wire runs through these areas presents another potential opportunity for monitoring. Whenever a cable harness carries sufficient electrical energy to start a fire, line-type heat sensors could be bundled with the harness. For long harnesses, localizing can be accomplished by using short sections of sensor wire with each section representing a specific segment of the cable run from front to rear of the aircraft.

Because of their size, it may not be practical or cost-effective to install monitors in all attic and cheek areas. Airframe designers should perform a failure modes and effects analysis and prepare a critical incident list to help determine which areas are vulnerable and should be monitored.

Closets and Storage Bins. Both heat and smoke sensors of the spot-type should be considered for coat and hanging garment bag closets, particularly those in which the garments are retracted mechanically into a concealed compartment. Line-type heat sensors might be considered for overhead compartments and can be installed in the same manner as for the cable harnesses discussed above. While closets and bins do not appear to be at high risk and are within range of human sensors, they are at least partially hidden. It is possible for a fire to grow, for a time, undetected. Each storage area design, therefore, should be examined carefully when considering sensor installation.

OTHER DATA INPUTS. An ACES fire management system depends primarily on sensing combustion products (heat and smoke) to determine the existence of a fire. There are other data, however, which might be surrogate indicators of fire or provide a reference for more precise interpretation of the sensor outputs. This information is essentially circumstantial evidence of the existence of a fire. The four most promising types of data relate to flight status, circuit breakers, electrical loads and hydraulic pressures.

The ACES can use these other data because they are already available on the digital data bus. The current generation of digital data buses is defined according to ARINC Specification 429-10 (1987). A further enhancement in the concept of digital information transfer is underway in proposed ARINC Specification 629. In essence, a digital data bus may be thought of as a party line on which specific pieces of digitally-encoded information are transferred from one "user" or subsystem to another. The information which the ACES would require is already coded on the bus. Therefore, the ACES software would merely have to request "delivery" of the desired data in order to make it available to a decision-making algorithm.

Flight status data such as vertical speed, outside temperature and baseline levels of heat and aerosol in sensed areas would be especially useful. Baseline sensing could occur automatically when the last aircraft door or cargo hatch was closed. The position of these doors and hatches is already included in monitoring systems. The main application of flight status data would be to

provide an explanation for observed changes in temperature or aerosol thereby either avoiding a false alarm or supporting the existence of a real incident.

Circuit breaker information can be extremely valuable in the event of short circuits or major overloads. For example, if a positive heat slope is detected in an area of electrical equipment and then a circuit breaker covering the same area trips, it is reasonable to conclude that a real fire/smoke incident is underway. If the breaker trips first, alarm criteria can be revised to react more quickly to increases in heat or smoke since there would be a greater likelihood that they were real.

Electrical load data can serve much the same purpose as circuit breaker information. Higher than normal current flowing in a particular piece of equipment or through a certain area could explain an increase in smoke or heat. Current flows can also be used to determine if certain equipment which could make smoke, such as galley ovens, are on or off.

Hydraulic fluid from a leak can ignite as a separate fire or fuel a fire in progress. The leak itself may be the result of a fire or of a failure in the system. In either case, monitoring hydraulic pressures which are already available on the data bus will provide additional valuable information to help resolve some uncertainties.

PROCESSOR. The analysis presented in the previous Section suggests that the best approach for ACES would be to operate on one of the 32 bit integrated processors being developed to run future avionics. Given the inherent fault tolerance of these processors and their fail-operational and fail-safe design, it would not appear necessary to run ACES redundantly on a second computer.

While the present study specifically excluded a detailed examination of retrofitting the system into existing aircraft, it should be noted that the processor hardware requirements of the ACES would not preclude a retrofit. A separate dedicated micro-processor could be added which would implement the ACES logic and sample the digital data bus on those aircraft such as the Boeing 767 and 757 and the Airbus A300-600, A310 and A320 which have them. The limiting factor would be the difficulty of installing the sensors and wiring them back to the central processor.

Installing an ACES with the sophistication suggested by the configuration in the present study would be unreasonable on older aircraft equipped with an analog data bus. However, the basic smoke/heat sensor approach and interpretation of analog sensor inputs could be accomplished with an added micro-processor and sensor retrofits.

The proposed ACES configuration assumes the existence of an additional processor as part of system maintainability and reliability. This is the built-in test equipment (BITE) system which has become virtually universal in new aircraft designs. Under a BITE system, failures of redundant, non-essential components are often kept transparent to the crew. The back-up system is automatically engaged, and the failure is logged on the BITE processor. Maintenance personnel can then interrogate BITE to determine corrective actions. Alternatively, the BITE can take action and advise the crew of the change in status.

The existence of a BITE system is relevant to ACES because it provides a mechanism to identify and correct sensor failures without the direct intervention of the flight crew. A failed sensor would be electronically "placarded" by ACES, which would also alter its logic flow to operate in the degraded mode. Thus, the ACES could function in a fail-operational mode and not affect the dispatch reliability of an aircraft design.

CONTROLS AND DISPLAYS. All of the analyses conducted for this study suggest that it would be possible and, in fact, desirable to use existing warning and status displays and input units for ACES. The ACES operation as discussed below is completely compatible with the master warning concept currently in use. ACES status messages are consistent with other information normally placed on the system display of "glass cockpit" aircraft. Likewise, ACES warnings can be presented on the same warning display used by other aircraft systems.

SOFTWARE.

The "intelligence" of the ACES system will come from the decision rules and algorithms contained in its software. The implementation of the software should be in the Ada language compiled for operation on the contemplated 32 bit integrated avionics processors. This will insure that the ACES is compatible with anticipated industry trends. Ada is also a good choice because code written in this language is easy to maintain and transfer from one operating environment to another.

ACES operation will be governed by the rules and logic flow designed into the system. An expert system such as ACES can be programmed to act in at least three distinct modes. The first might be termed "advisory mode" and would involve the ACES collecting data, deciding if a problem exists and notifying the crew of the problem and its type. A second mode might be called "recommend." In this mode, in addition to advising the crew of the problem, the ACES would retrieve and display recommended actions or checklists and verify that they were performed correctly. In "automatic" mode, ACES would not only advise and recommend but carry out all of the checklist items without intervention by the crew.

In some current implementations of intelligent systems, the system operator is permitted to select the mode of operation . For example, the Intelligent Air Attack System being developed for the U.S. Navy's F/A-18 allows the pilot to select a pure advisory mode, an advisory mode with special alerting of deviations from plan, a recommend mode with the system taking action after pilot confirmation and a fully automatic mode (Lind, 1987). This flexibility was considered necessary by pilots in a combat environment.

An ACES operating in advisory mode would be optional, since it would not address all of the identified problems. In particular, it would do nothing to shorten the time to locate and access the appropriate checklist. A fully automatic ACES, within the state-of-the-art, could detect a fire, apply all prescribed countermeasures and even assume command of the aircraft. This approach, not unexpectedly, proved completely unacceptable to the pilots and airline operating personnel contacted during this study. It is also significantly more complex and would require extensive development time.

Since, for ACES, an advisory mode is sub-optimal and an automatic ACES is unacceptable, the assessed configuration assumed operation only in a recommend mode. Within this mode, the ACES would be tasked with detecting fires and discriminating them from false alarms, presenting alerts and warnings to the crew, accessing checklists and assisting in their accurate completion. The actual operation of an ACES would be governed by a set of decision rules and algorithms. The critical design effort for an ACES would likely explore such rules as:

1. Boolean logic - The combination of sensor and circumstantial data to reach a conclusion using deductive reasoning.

2. Pattern recognition - The use of experimental data on fires to quantify likely problems so that their signatures could be recognized.

3. Absolute thresholds - The determination of the smoke and heat threshold or redline values as a function of relevant flight phase and mission information.

For the purpose of a technology assessment, however, it is not possible to develop a full set of rules. If the ACES concept is feasible, it should be able to show merit based on a simplistic or "top level" logic flow. Figure 4 shows the ACES logic flow used to assess the potential benefits of ACES in the 13 fire scenarios developed during this study. This flow makes use of four types of information:

1. Baseline values - The ambient conditions at a defined baseline time which for the purposes of this analysis was assumed to occur when the last door or hold was closed.

2. Smoke level - The amount of aerosol measured by an appropriate sensor.

3. Heat level - The temperature as measured by an appropriate sensor.

4. Circumstantial evidence - Data on flight dynamics, circuit breakers, electrical loads, etc. which can be used to confirm a fire.

The simplified flow in Figure 4 does not consider fire signature matching through curve fitting to previously identified growth rate values. It depicts the deployment of a dual smoke/heat sensor battery, although the logic flow would be similar for only a single sensor type. Also, it is truncated so that the flow shown stops when a sensor failure or an alarm condition is established. An actual ACES would continue to function appropriately in both events.

The illustrated ACES logic assumes that the system has three states:

1. Normal - Monitoring is taking place but no abnormalities are detected.

2. Alert - Something abnormal has been detected but the system has not concluded that an emergency exists. This state results in more stringent monitoring criteria such as reducing the thresholds for heat or smoke. Depending on the final design philosophy, alerts could remain transparent to the flight crew or be reported as cautions on the warning display.

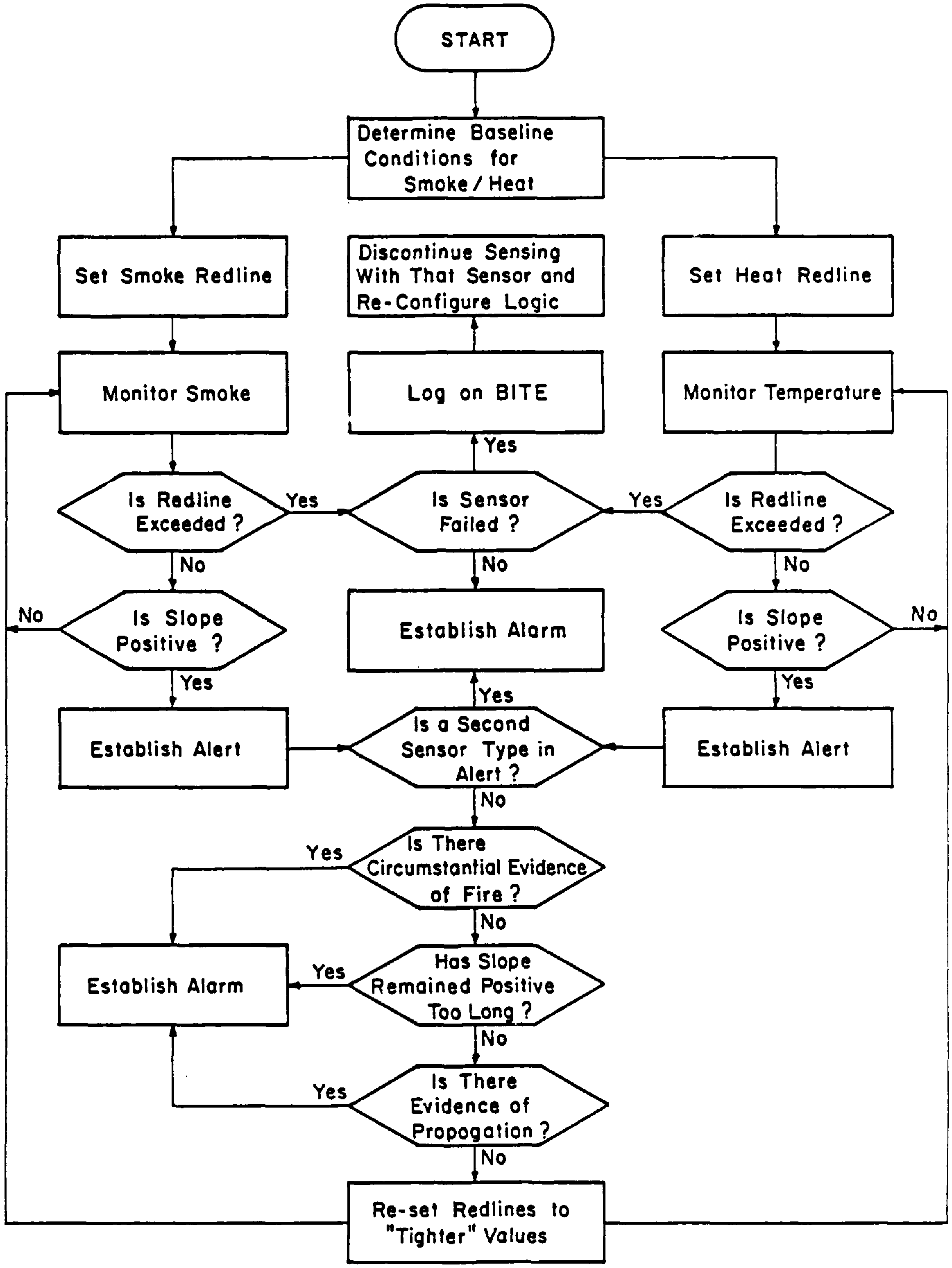

FIGURE 4. ACES LOGIC FLOW

3. Alarm - An emergency has been detected. This emergency may be a fire or smoke incident or another problem which the ACES cannot discriminate from a fire. In either case, an emergency response by the crew is indicated.

An actual ACES implementation would define levels of alert and alarm and associated system responses based on estimated fire severity. This added sophistication would enhance the system's performance but was not considered a necessary part of ACES for a feasibility assessment. In any alarm or alert state of the ACES system, there is the implication that the system would display, in some way, the nature of the alarm or alert (e.g., smoke only or heat only). The extent of information displayed would depend on the requirements established by each operator for each aircraft type and use. In all cases, however, the information must provide necessary and relevant support for crew decisions and actions in each detected condition. If no crew action is possible or desired, workload may be unnecessarily increased by the need to read and interpret extraneous ACES information.

The ACES logic as shown in Figure 4 is guided by three basic principles:

1. "Redline" emergencies - Thresholds or "redlines" will be established for all sensors. If a measurement is confirmed beyond the redline value, ACES will always produce an alarm, although the nature of the alarm may vary.

2. Variable redlines - Sensor thresholds for both heat and smoke will be established based on dispatch conditions, the particular nature of the space being monitored and the flight's mission. They are subject to change to yield a more rapid alarm if sensor data indicate a suspicious situation.

3. Multiple criteria - Unless a redline has been reached, the ACES will not generate an alarm until warranted by at least two criteria.

The start of the logic flow involves establishing initial redlines from baseline conditions for the smoke and heat sensors deployed throughout the aircraft. The need for establishing redlines for each flight arises from the wide range of ambient conditions which can be experienced at dispatch. For example, the temperature in a cargo hold after departing from an extremely hot desert field would be expected to decrease for some time after takeoff. Conversely, cargo hold temperatures after departure from an arctic region in the winter can be expected to rise quite rapidly after the door is closed.

Sensing of the baseline conditions can take place automatically when triggered by an appropriate event such as the closing of the last door or hatch. Once the baseline is established, the ACES processor, using appropriate algorithms, would translate the conditions to specific smoke and heat redline values and monitoring can begin.

The monitoring logic for smoke and heat is identical as shown in Figure 4. Sampling of each sensor would take place at a rate consistent with the activity on the data bus and the priority assigned to the ACES program in the multi-function processor. Even if the ACES is given a relatively low priority, a sampling rate on the order of once per second would likely result. While this is relatively slow compared to the rate for other avionics subsystems, it is fast enough to accomplish all of the ACES system objectives.

The first decision criterion is whether or not the sensor output exceeded the redline value. If this occurs, it can either signal a sensor failure, an anomalous condition not covered by the ACES logic or a true emergency. Some sensor failures can be detected by the shape or pattern of the increase through the redline. For example, if a sensor produces essentially a square wave output and jumps from a steady-state to redline instantaneously, a sensor failure is virtually certain. Even the fastest possible fire growth would not produce a sensor output with infinite slope.

If a failure is confirmed, the sensor failure would be logged on the BITE system for repair at the earliest opportunity. The sensor would then be placarded as inoperative by the ACES and removed from the system. The system logic would be updated to continue monitoring without the failed device. This entire process could remain transparent to the flight crew if the degradation did not seriously impact flight safety. Alternatively, a status message concerning the reconfiguration could be displayed. Actions to be taken, if the loss of the sensor left an area totally unmonitored, would depend on decisions made at the time the aircraft and ACES system were certificated.

Anomalous conditions might involve such things as a slow increase in water vapor from a pressurization leak or a runaway heating system. In an actual ACES system for which a complete aircraft failure modes and effect analysis was available, it may be possible to separate these conditions from real emergencies by using other data sources. Since in this feasibility study it was sufficient to postulate only a simple, "basic" ACES, it was decided to treat these anomalies as emergencies.

In the event that a redline is exceeded and sensor failure cannot be confirmed, an alarm situation exists. In fact, three separate alarms might be involved:

1. A smoke alarm if only the smoke sensor exceeded redline;

2. A heat alarm if only the heat sensor exceeded redline; and,

3. A <u>fire</u> alarm if both exceeded their respective redlines.

Procedurally, it is assumed that any one of these alarm conditions would require the crew to follow existing checklists and to divert the flight to the "nearest suitable airport." The urgency of that diversion and decisions concerning a rapid descent, maximum effort stop and emergency aircraft evacuation would likely vary depending on the nature of the alarm.

If a redline has not been breached, the second criterion to be applied would look for a positive slope on the sensor output. Statistically, quality control theory and time series analyses provide many ways to examine trends. The choice of a particular technique to be used is beyond the scope of the present effort. Even an extremely conservative approach, however, such as waiting for five consecutive samplings which were at least three standard deviations above the previous long-term average, could detect a positive slope in 30 seconds or less.

Detection of a positive slope would indicate an <u>alert</u> condition. If a second sensor type (fire or smoke) in the same physical area also was in alert, an <u>alarm</u> condition would result. Moreover, the presumption from a dual alert is that a fire is in progress.

The corroboration of an alert from one sensor by another type of sensor is not the only means ACES can use to to determine the existence of an alarm condition. Three other means of verification are available. These are shown in Figure 4 and described below::

1. Circumstantial evidence - Information on such things as circuit breaker trips and electrical loads which is available to ACES on the data bus can be used to confirm a fire alarm condition. Obviously, the specific tests and data required would have to be carefully defined and be specific to the aircraft type as well as the area being monitored. If this evidence exists, ACES can move a single sensor alert to an alarm without the need for a second sensor-based alert. Circumstantial evidence may be the primary validation information available for those parts of the aircraft monitored by only a single sensor or in the case of a sensor failure.

2. Slope duration - As discussed above, the determination of the existence of a positive slope can be made quite rapidly. It takes additional time, however, to forecast the magnitude of that slope and estimate when it will breach the redline. In the event of a positive but relatively small slope, significant time may be wasted waiting for the sensor value to reach redline, even if the redline limit is severely reduced. Therefore, once sufficient data are available to the ACES to forecast with statistical assurance that the redline will be exceeded, an alarm condition is warranted. The detailed design of an ACES would have to examine alternative decision rules related to sensor slope to determine exactly the criteria to be used.

3. Evidence of propagation - The dilution of combustion products by the air conditioning system may delay an alarm. In order to recover some of the lost time, the sequential response of sensors in adjacent, monitored areas can be used. For example, if heat begins a positive slope in one cheek area and, after a delay of appropriate duration, starts to rise in the adjacent cheek areas, an alarm condition is suggested.

When an alert is established and none of the verifying criteria are met, the ACES response is to reset its redlines to "tighter, more conservative values. This will shorten the response time to establish an alarm if corroborating sensor values are detected or if the output of the sensor which triggered the alert continues to climb. Redline values can be iteratively reduced until an alarm condition is achieved or a pre-established minimum is reached. They can also be reset to higher levels if the sensor output begins to show a negative slope.

The ACES logic flow can be examined generically with respect to the nine cell matrix for analog sensors presented earlier (page 29). In that matrix, cells A, B, C, D and G all involve sensor values above redline. Therefore, ACES would generate an alarm condition. For cell A in which both smoke and heat redlines have been exceeded, a definite fire alarm is indicated. Likewise, cells B and D, which are characterized by a redline on one sensor type and an increase on the other, would warrant a declaration of a fire.

The conditions indicated by cells C and G involve one sensor type at redline with the other showing no change above steady-state. These would generate a specific smoke or heat alarm condition which would indicate to the crew that a redline had been exceeded and emergency action was warranted but that the data could not be definitively resolved as a fire, sensor failure or anomalous condition.

The condition in cell E has both sensors showing a positive slope. This is one of the defined conditions for an ACES fire alarm. A positive slope on one sensor and no response on the other is indicated in cells F and H. This is ambiguous information which would cause the ACES to change to alert status. Redlines would be reduced as the system monitored for further indication that a fire was in progress. Cell I is a normal condition and would not result in an ACES system response.

The ACES configuration just presented describes a conceptual system in sufficient detail to examine its operation under the specific circumstances of the 13 developed fire scenarios. These scenarios and the application of the ACES to them are presented in the next Section.

SCENARIO BASED ACES ANALYSIS

The 13 scenarios used in this analysis each include the following six parts:

1. The scenario description is a narrative of the flight, the incident, crew responses and the outcome. It is in essentially the same format and level of detail as in NTSB and similar investigatory reports.

2. The fire narrative is a description of the ignition and propagation of the fire. The times of critical events (e.g., ignition, active flaming and total obscuration by smoke) are estimated. The nature of the fuels, the path of propagation, flame temperature, etc., are also identified (if possible) in this narrative. Illustrations of fire/smoke development accompany some of these narratives. For false-alarm of smoke-only scenarios, there are no detailed fire narratives.

3. The smoke-temperature signature graph depicts the scenario on an elapsed-time basis. Fire-temperature and smoke-density changes are plotted. Smoke density is a qualitative estimate developed to help determine the approximate time at which sensors would be triggered.

4. The problem analysis is both a description and a critique. The model of in-flight fires described earlier (detection, localization, etc.) provides the basis for the description. For each part of the model, the scenario events are described briefly. This is followed by an evaluative statement about how well each part of the model was carried out.

5. The ACES analysis is an adaptation of the problem analysis in which it is assumed that an appropriate, functioning ACES system was present. Appropriate crew procedures have been hypothesized for the ACES and are used in this analysis. An evaluation is made of the benefits that would result from the ACES system.

6. The timeline summary table shows each key event in the scenario, the time at which it occurred and the phase of the flight in which it occurred. This is arranged in a timeline at the bottom of the table. Above this are shown combustion evidence, circumstantial evidence, actual detection and actual response related to each event. The benefits which would have been realized if the ACES concept had been implemented are shown at the top of the table. Each ACES benefit is aligned with the time at which it would have occurred.

The table does not show an entry in every category for each event. For example, an event which took place in a cargo compartment would probably not create circumstantial evidence, so no entry appears in that category. A blank in the table, then, denotes that the category is not applicable to the event. When the word "same" is used, it denotes that the entry immediately to the left has not changed. The timeline summary table appears at the end of each scenario.

SCENARIO 1 - FIRE IN AFT BAGGAGE COMPARTMENT.

SCENARIO 1 - DESCRIPTION. A wide body tri-jet aircraft with a Flight Crew of three (Captain, First Officer and Flight Engineer) and eleven Attendants in the cabin was scheduled for service between Denver Stapleton International and Boston's Logan Airport. There was a large amount of bulky baggage (skis, packs, etc.) which was stowed in the aft baggage compartment. Baggage loading and ground service was completed with no unusual events at 1730. The Flight Crew had earlier completed a visual inspection and performed a pre-flight checklist with no abnormal indications.

The flight departed the gate at 1750. Pre-takeoff checklist was completed normally and the flight was airborne at 1808. Hand off was made to Departure Control which vectored the flight out of the terminal area on course and passed control to En Route Control at 1811 when the flight was eastbound abeam Fort Morgan on its cleared flight plan. The weather at this time was clear, visibility at Denver was 2 miles, wind at the surface was 270° at 10-15 knots, thin scattered clouds at 5,000 feet in the flight area and at Stapleton. At 1815 passing through Flight Level 200, the aft compartment smoke alarm (B loop) was activated along with the master warning. The Captain reset the master warning and requested the Flight Engineer (FE) to interrogate the A loop; the A loop tested normal. The Flight Crew began to search for abnormal procedures relative to the aft compartment smoke alarm. At 1816 (Flight Level 220) the A loop alarm activated. The Captain reset the master warning and directed the FE to go to the rear of the passenger compartment to make a visual inspection and to attempt to detect the odor of smoke.

At 1819 the aft compartment smoke alarm procedures were located under "Emergencies" not "Abnormal Procedures," where the Flight Crew first looked for them. These procedures included a recommendation to land at the nearest available airport. The FE returned to the flight deck at 1819:30 and confirmed the odor of smoke in the aft end of the passenger compartment. The FE said that there was a fire in the aft baggage compartment. The Captain and the First Officer then discussed whether or not to declare an emergency. At 1820 the Captain requested and was granted a reverse course back to Denver. At 1824 a Flight Attendant told the Captain there was fire in the passenger cabin. At 1826 the Captain told ATC there was fire in the cabin and was given clearance to descend and was cleared number-one for a straight-in approach and landing. Contact was made with the Stapleton tower which confirmed that fire trucks would be alerted and in place adjacent to the landing runway. It was determined that there was no satisfactory alternate airport and during the return to Denver, the passengers were briefed on emergency procedures. At 1826 the number two throttle became "stuck." The Pre-landing Checklist was initiated at 1830; the flight at this time was 28 miles out. There continued to be smoke detector warnings from the aft baggage compartment. The passengers were now reacting violently, and during the remainder of the approach both the

Flight Crew and the Cabin Crew attempted to quiet and control them. Between 1824 and 1827 the Cabin Crew collected all available hand extinguishers and attempted to suppress the fire. The attempt was not successful. The passengers were not briefed on emergency evacuation but had been instructed and were coached on emergency landing procedures throughout the approach. The initial Pre-landing Checklist was completed at 1833: all items were completed normally except that controls for engine 2 were "stuck." Engine 2 was shut down on final. The final Pre-landing Checklist was completed at 1834. At 1836 the flight touched down and the cockpit voice record ended. The flight made a full roll-out upon landing and taxied off the runway and stopped at 1838. The ground communication showed that the Captain then shut down the two active engines at 1841 and said that he was ordering passenger evacuation. The last communication from the flight came at 1842 when the Captain confirmed that he was attempting to evacuate passengers.

There was no evidence of evacuation from outside the aircraft. Smoke and later flame engulfed the aircraft. There were no survivors and the aircraft was destroyed by fire.

SCENARIO 1 - FIRE NARRATIVE. A fire of undetermined origin began in the forward left side of the aft cargo compartment (a modified Class D area) as shown in Figure 5A. The fire initially involved baggage and cargo. The most probable time of ignition was just prior to takeoff, approximately 1800. At 1808, the first smoke was generated. As smoke circulated throughout the compartment it mixed with air provided by the animal air system and was diluted and partially removed (Figure 5B). This dilution and removal of smoke delayed the smoke concentration from reaching the alarm threshold. At 1810 the gas temperature approximately 5 feet from the burning luggage at the ceiling of the cargo compartment reached approximately 150°F. At 1814 the temperature at the ceiling approached 200°F and a minute later smoke detector B went into alarm, followed a minute later by detector A. At or about the time of the detector operation, flames were produced actively from the burning luggage and contacted the cargo liner (Figure 5C). At 1818 smoke entered the space between the cargo liner and the hull of the aircraft and proceeded upward, entering the passenger compartment. Flames from the burning luggage were now in direct contact with the aluminum hydraulic lines of hydraulic system B. At 1820 hydraulic system B experienced a failure and a high pressure spray of hydraulic fluid ignited; these flames impacted the cabin floor at the top of the cargo compartment, as shown in Figure 5D. Estimated temperature at the ceiling of the cargo compartment reached 1500°F. At 1824 flames were seen in the cabin by a Flight Attendant. The Attendant reported the presence of the fire to the cockpit. The fire continued to escalate during approach, landing and taxiing. After the aircraft stopped, there was no evidence of an attempt to evacuate passengers. The interior of the aircraft became totally engulfed in flames and was subsequently destroyed. The smoke-temperature signatures are shown in Figure 6.

SCENARIO 1 - PROBLEM ANALYSIS.

Background. This incident involved a serious fire in a baggage compartment in the aft section of a wide body tri-jet. The fire resulted in destruction of the aircraft; there were no survivors.

Detection of the Fire. The first detection was of smoke by an automatic smoke sensor which produced a visual and audible display in the cockpit. It

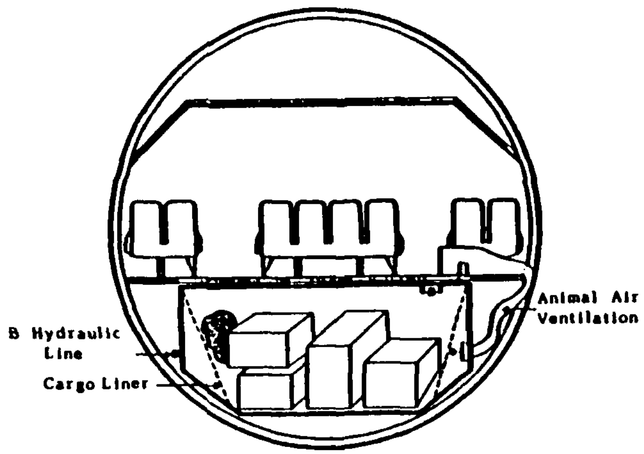

FIGURE 5A. FIRE STARTED FORWARD LEFT SIDE AFT CARGO COMPARTMENT

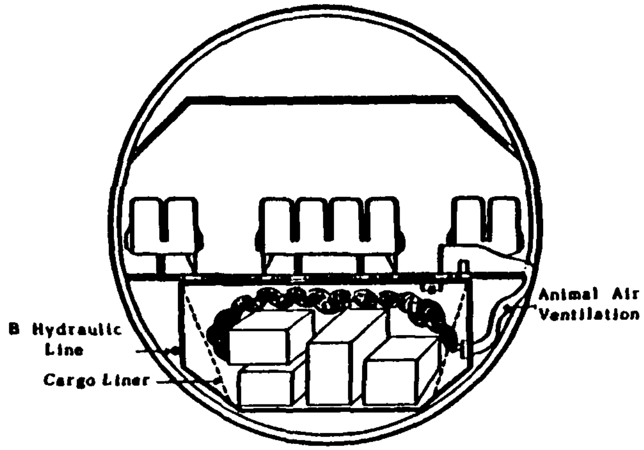

FIGURE 5B. SMOKE DILUTED BY AIR VENTILATION SYSTEM

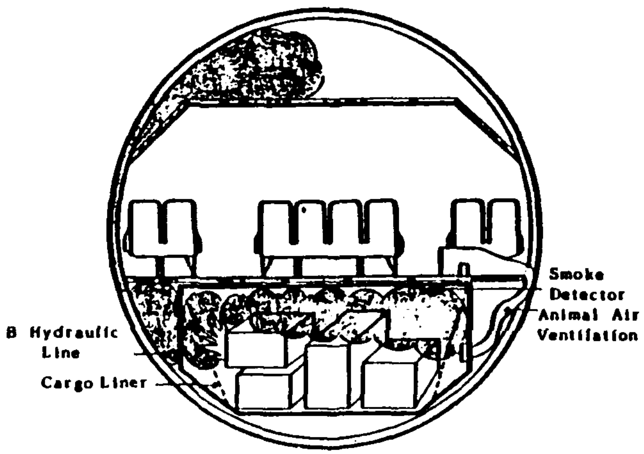

FIGURE 5C. SMOKE DETECTOR ALARMS, FLAMES CONTACT LINER

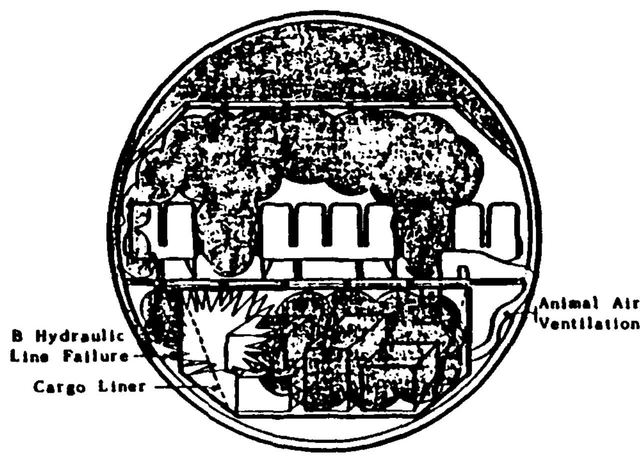

FIGURE 5D. B HYDRAULIC LINE FAIL- URE CREATES SPRAY FIRE

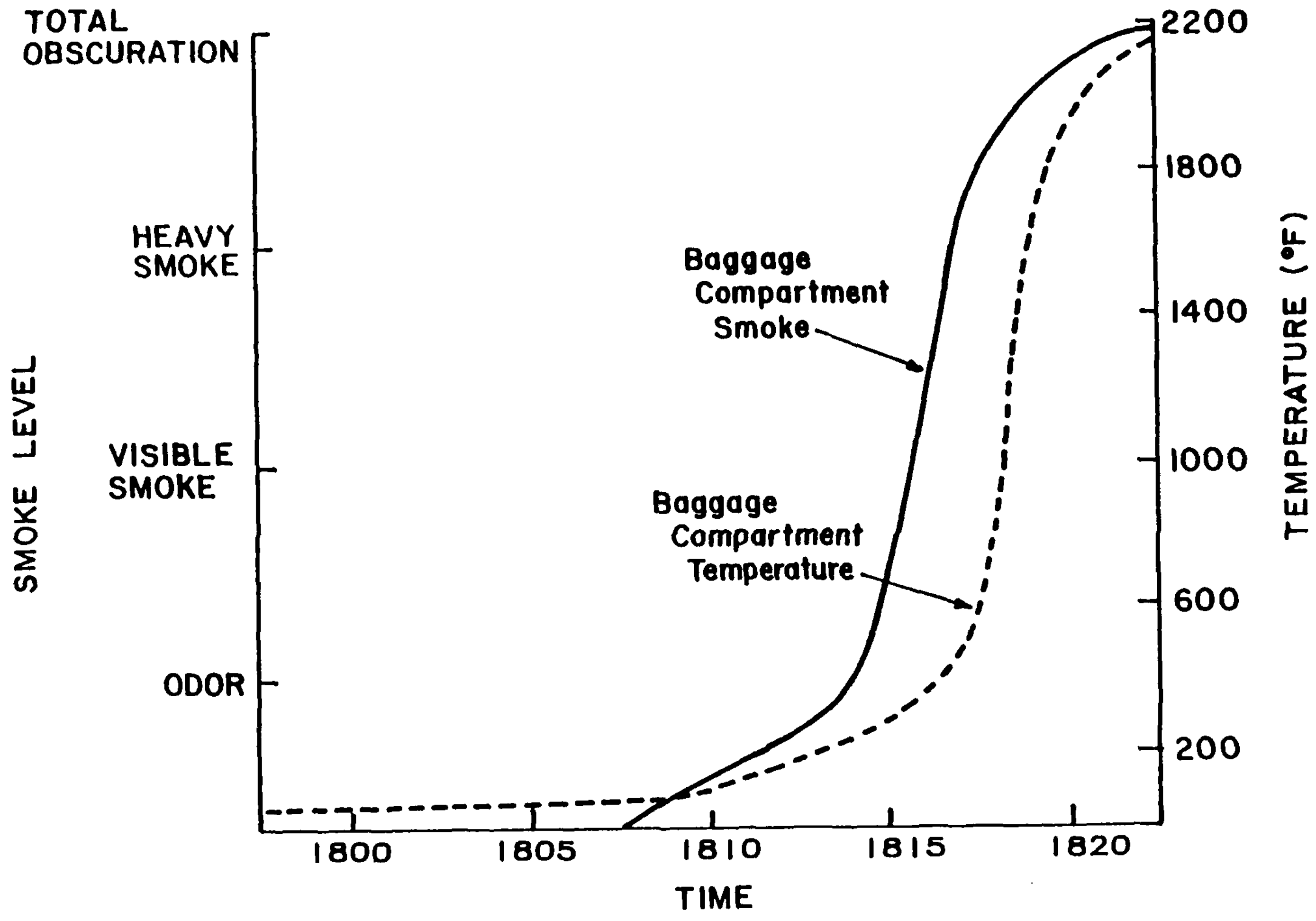

FIGURE 6. SCENARIO 1: SMOKE-TEMPERATURE SIGNATURES

appears that this detection came only after the fire had developed to a flaming stage. A second smoke sensor went off one minute after the first. Four minutes after the first sensor had gone off, the odor of smoke was detected in the passenger cabin. Five minutes later (nine minutes after the first smoke sensor) there was visible fire in the cabin. Not only was the fire apparently well developed before the first detection was made, but response was further delayed by the Captain's unwillingness to accept the first smoke sensor alarm without confirmation. Further delay in responding occurred when the smoke warning checklist was not promptly located.

In summary, had an immediate response (declaring an emergency and reversing course) been made to the first smoke sensor signal, five minutes could have been saved.

Localization of the Fire. The smoke sensor alarms gave positive indications of the location of the fire: aft cargo compartment, both B and A loops. The crew attempted to confirm the sensor alarm and location of the fire, but they apparently did not correctly identify the location at which the fire originated. When the fire became visible in the passenger compartment (nine minutes after the first smoke alarm) an unsuccessful attempt was made to suppress it. The crew did not accept the initial detection (smoke sensor) and thus could not be said to have correctly localized the fire. This is probably inconsequential since the aircraft had no fire suppression capability in the area.

Identification of Fire Severity. Once the fire became visually apparent, the crew's identification was correct: fuselage and other material in or near the cabin floor and cargo compartment were burning intensely. It appears that the Captain initially questioned whether the smoke alarm was valid and did not accept the fact that the fire was severe until it erupted into the passenger compartment.

Evaluation of Situation and Choice of Actions. Even with the fire progressing into the cabin area, the crew apparently did not fully appreciate the risk. Suppression activity was not initiated until well after the fire was visible in the cabin. The Flight Crew continued to check smoke sensor loops as if to confirm the fire location. The Captain never ordered emergency evacuation briefing for the passengers. From the record it would appear that the Captain never made decisive, effective responses throughout this incident. Risk assessment has to be judged inadequate. With regard to countermeasures, the critical problem is that the use of extinguishers was neither timely nor warranted as the primary response. Given the advanced state of the fire it is probable that no suppressive action would have been effective. If, however, the initial response had been made promptly, there might have been more time once on the ground to evacuate passengers. If the extinguishers had also been applied without delay, the aircraft might have been on the ground with much less fully developed burning. Thus, there might have been the opportunity for emergency evacuation.

Conclusions. In this incident a fire was detected only after it had apparently developed to a flaming state. This situation significantly reduced the time available for making an effective, safe response. The problem was then exacerbated by the Captain's delaying his decision to declare an emergency and return. Time was also lost in looking for smoke warning checklists and in

sending the Flight Engineer to evaluate the fire visually before initiating the return. Once the flight had returned, further delay occurred when the Captain made a routine, full roll-out, landing and began to taxi toward a parking area. A maximum effort stop after landing followed by immediate emergency evacuation were clearly the actions appropriate to this incident. It is possible that during the approach and landing the Captain (as well as all others on board) was less than fully conscious due to smoke/fumes inhalation.

<u>SCENARIO 1 - ACES ANALYSIS</u>. The analysis of this scenario reported in the fire narrative shows that smoke probably appeared in the aft baggage compartment at about 1808. The ACES system would likely have sensed smoke soon after it appeared. It would have then almost immediately determined a positive, increasing rate of rise. This would have established a smoke alert and the system would have set a more stringent redline for heat. Meanwhile, the ACES heat detector would have sensed a heat level above ambient and determined a positive and slowly increasing rate of heat rise. The simultaneous alert for both heat and smoke would then have resulted in an ACES alarm, i.e., a true fire condition. This alarm could have appeared as early as 1809. Assuming that the crew responded with the correct emergency procedure and lost no time in further analysis, it is estimated that the aircraft could have begun descent back to Denver at 1811. The analysis suggests that this is a conservative estimate of the time needed to react to the alarm, request and receive ATC clearance to return to Denver and make a faster than standard rate 360° turn.

The ACES benefit then is that the aircraft could have been on the ground at 1814. Fire would not have appeared in the passenger cabin by this time (it was reported at 1824). The crew as well as the passengers would have been exposed to smoke and fumes a significantly shorter time than in the scenario and they could be expected to respond more quickly in evacuating the aircraft. Further, the ACES system would have displayed the correct emergency procedures including both a maximum effort stop and emergency evacuation. That display might have helped ensure that both these procedures were briefed and followed which was not the case in the scenario.

In summary, the ACES system would have provided up to 22 minutes in which passenger and crew evacuation could have been attempted. The actual touchdown was at 1836: as estimated here, the ACES system could have allowed touchdown at 1814. Additionally, the ACES would have forced displays of emergency procedures relieving the crew of the stress of selecting and locating procedures and probably increasing the likelihood that they would be performed.

TABLE 1. SCENARIO 1 - TIMELINE SUMMARY

ACES BENEFIT		System alarm at 1809; begin return at 1811						Return to airport 22 minutes earlier	
ACTUAL RESPONSE			Test Alarm A; look for checklist	Make visual inspection		Check-list located and read		Turn back	
ACTUAL DETECTION			Smoke sensor	Same			FO sensory	Same	Flight Attendant
CIRCUMSTANTIAL EVIDENCE AVAILABLE						Loss of B line hydraulic pressure	Odor	Same	Visible flame
COMBUSTION EVIDENCE AVAILABLE			First flames; smoke and heat	Flames contact cargo liner; increasing smoke and heat	Increasing smoke and heat		Increasing smoke; intense heat	Same	Same
EVENT	Probable ignition time	First smoke generated	Smoke Alarm B	Smoke Alarm A	Cargo liner failure	B Line hydraulic failure	Smoke odor in cabin	Request return to Denver	Fire in cabin
TIME	(1800)	(1808)	(1815)	(1816)	(1817)	(1818)	(1819)	(1820)	(1824)
FLIGHT PHASE	Taxi	Takeoff	Climb	Climb	Climb	Climb	Climb	Descent	Approach

TABLE 1. SCENARIO 1 - TIMELINE SUMMARY (Continued)

ACES BENEFIT	Return touchdown at 1814 hours				
ACTUAL RESPONSE	Deploy extin-guishers	Look for checklist			
ACTUAL DETECTION		Flight Crew			
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Same	Position of con-trol levers		Visible flame	Same
COMBUSTION EVIDENCE AVAILABLE	Same	Same	Same	Same	Same
EVENT	Deploy extin-guishers	#2 Throttle stuck	Touch-down	Taxi and park	Attempt evacuation
TIME	(1825)	(1826)	(1836)	(1838)	(1842)
FLIGHT PHASE	Approach	Approach	Landing	Parked	Parked

SCENARIO 2 - LAVATORY FIRE.

SCENARIO 2 - DESCRIPTION. A narrow body twin-jet aircraft was en route from Chattanooga to Chicago at Flight Level 310. The crew consisted of Captain and First Officer on the flight deck and three Flight Attendants in the cabin. There were 45 passengers on board (about half of the total capacity). At 1654 three circuit breakers associated with the aft lavatory's flush motor tripped. The Captain attempted to reset the breakers but was unsuccessful and subsequently reported that he assumed that the motor had seized or been jammed by foreign matter in the toilet. Again at 1705, the Captain attempted to reset the same breakers and was not successful. At 1708 when the flight was approaching Bowling Green, a Flight Attendant was alerted to the odor of smoke by a passenger and discovered smoke and heat in the left, aft lavatory. The lavatory was not equipped with smoke detectors, but had Halon extinguishers in the trash chute and bin. It was subsequently determined that these extinguishers had activated. The Captain was notified and a CO_2 extinguisher was discharged into the lavatory at a seam in the cabinet from which smoke was issuing.

Immediately after attempting to extinguish the fire, the Flight Attendants moved the passengers forward and opened the air vents over the passenger seats. The Flight Attendant in charge went to the flight deck and told the Captain that there was a fire in the aft lavatory and that the Attendants had gone to put it out. The Captain directed the First Officer to go aft and investigate. The First Officer was unable to get to the lavatory because of the smoke which had infiltrated the cabin: the time was 1710. The First Officer did not have a smoke mask or portable breathing oxygen with him. At 1710:30 he returned to the flight deck and reported to the Captain that he had been unable to penetrate the smoke and suggested an emergency landing. The Captain declined to declare an emergency. The Flight Attendant in-charge and the First Officer told the Captain that they thought the smoke was clearing. At 1712, the First Officer returned aft with a smoke mask; he discovered that the lavatory door was hot to the touch and decided not to open it and told the Flight Attendants not to open it. While the First Officer was aft, the Flight Attendant again told the Captain that the smoke was clearing. This clearing apparently occurred when the lavatory door was closed after the discharge of CO_2. At 1713 the First Officer returned to the flight deck, told the Captain that he had decided not to open the lavatory and again recommended an emergency landing.

Just after the First Officer's report, the master warning indicator showed that the left AC and DC systems had both lost power. At 1714, the Captain called ATC and reported an electrical problem and virtually simultaneously, the aircraft's radar beacon signal stopped due to the power loss. At 1715 the emergency AC and DC buses lost power taking out the attitude and directional indicators on both the left and right instrument panels. Battery power was applied through the emergency power switch. Stablizer trim was lost. At 1716 the First Officer had returned to his position on the flight deck. At the same time the Captain declared an emergency to ATC and was granted clearance for an immediate descent. All affected traffic was notified. ATC informed the flight that weather in the immediate area was broken to overcast at 10,000 feet, wind west at 15-20 knots, unlimited visibility. ATC also informed the flight that Louisville was now the closest diversion field at approximately 75 miles. Nashville was also suitable but was now approximately 90 miles south of

the flight's position. Clearance was granted at 1717 for a direct emergency descent to Louisville. The Cabin Crew briefed the passengers on emergency evacuation procedures.

The flight was unable to provide all of the information requested by ATC (fuel on board, passengers, etc.) because of the difficult emergency operation with smoke penetrating the flight deck, no stabilizer trim and no directional gyros. ATC encountered some difficulty in making positive radar identification because the flight's beacon was inoperative. Positive identification was eventually made, and ATC provided steering control (no-gyro approach). The flight crew made a successful, but difficult, emergency descent and approach; they successfully penetrated the overcast layer and, at 1724, the flight reported being VFR at 3,000 feet. ATC informed the flight it was 20 miles from Louisville and directed it to descend to 2,000 feet and continue its straight-in approach. ARFF vehicles were in place alongside the landing runway and the runway/approach lights were turned to full intensity. At 1726 the Captain reported the field in sight. The approach was completed with ATC assistance and at 1728 the flight touched down.

The Captain made a maximum effort stop and the emergency engine shutdown checklist was completed. The forward cabin doors as well as one of the left and both right side overwing exits were opened and both forward door evacuation slides deployed and inflated. Eighteen passengers and the Cabin Crew safely evacuated the aircraft; the Flight Crew attempted to enter the passenger cabin and assist in evacuation but were driven back by smoke and heat. The Captain and the First Officer left the flight deck through the cockpit windows.

It was later determined that a flashover occurred in the passenger compartment about one minute after landing filling the aircraft with virtually impenetrable smoke and intense heat. Firefighting and rescue efforts were severely hampered. The aircraft was destroyed.

SCENARIO 2 - FIRE NARRATIVE. At approximately 1649, the fire began as a result of arcing of the AC generator feeder cables in and around the vicinity of the wiring harness to the toilet flush motor, left rear lavatory. At 1654 the flames from the burning debris and insulation burned through the flush motor wiring harness resulting in the simultaneous tripping of the circuit breakers for all three phases of the motor (Figure 7A). Smoke from this fire was distributed throughout the cheek area and above the passenger compartment as shown in Figure 7B. As the fire grew, it penetrated the amenities cabinet at the aft and the lower right hand corner, igniting stored amenities material such as bags and tissue. Because the air supply was limited to the small volume inside the amenities cabinet, the fire developed fairly slowly, but smoke began to drift into the lavatory itself. Although this smoke was initially drawn off by the sanitary ventilation system, the lavatory eventually filled with a light haze of smoke. At 1708, smoke drifted out of the cracks around the lavatory door and was first detected by a passenger who reported it to a Flight Attendant. It is estimated that the air temperature in the lavatory at this time was approximately 70°-80°F and the temperature inside the amenities compartment was between 100° and 200°F. The lavatory door was opened and within a minute a fire extinguisher was discharged and the lavatory door was closed again. Although the smoke seemed to be clearing in the passenger compartment, the fire grew inside the amenities cabinet, which caused the

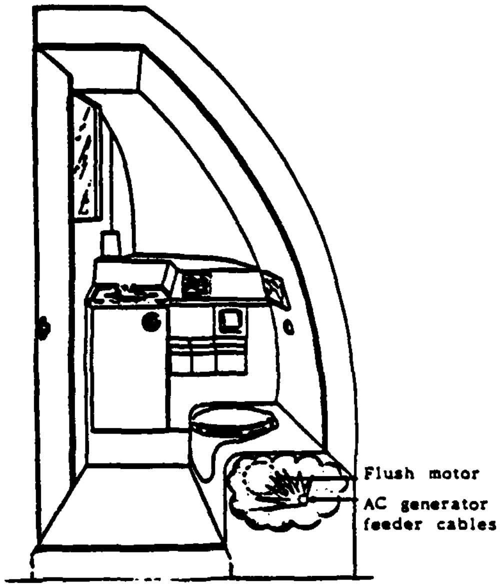

FIGURE 7A. FLAMES CONTACT FLUSH MOTOR CABLES

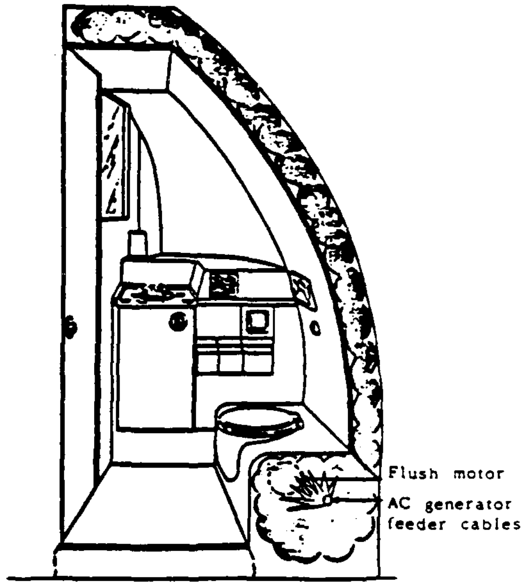

FIGURE 7B. SMOKE RISES INTO SIDEWALL AND OVERHEAD AREAS

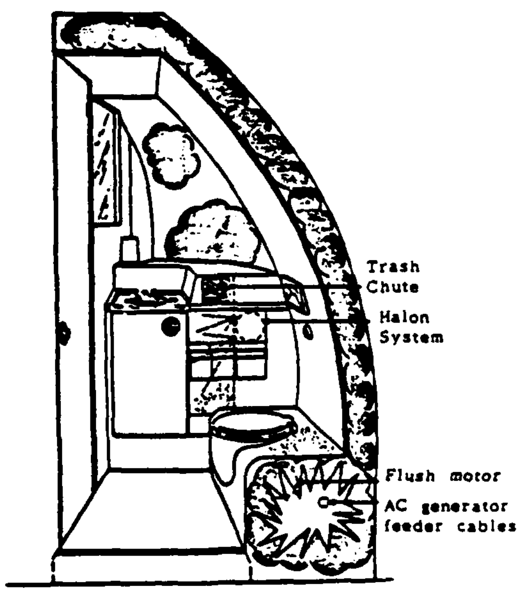

FIGURE 7C. GAS TEMPERATURE IN TRASH CHUTE TRIGGERS HALON SYSTEM

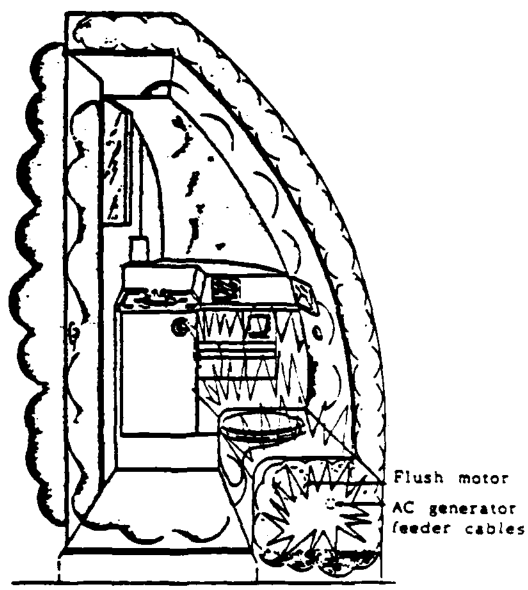

FIGURE 7D. FIRE PENETRATES WALL: SMOKE ENTERS PASSENGER CABIN

continued build up of smoke in the lavatory. At 1710, flames from the fire entered the lavatory. At 1711 the gas temperatures in the trash chute in the amenities compartment triggered the Halon system (Figure 7C). It is estimated that gas temperatures of approximately 250° F are necessary to operate the Halon system. The temperature rose rapidly in the lavatory, and, at 1712, it is estimated that it reached 400-500°F making the outside of the door too hot to touch. Somewhere between 1723 and 1728 the fire penetrated the lavatory wall exposing the passenger compartment to large quantities of black smoke and heated gases (Figure 7D). Temperatures at this time were between 1,000°F and 1,200°F in the lavatory. At 1730, the aircraft rolled to a stop and the doors were opened. One minute later there was a flashover which began in the rear of the cabin and moved forward, engulfing the entire cabin. The smoke-temperature signatures are shown in Figure 8.

SCENARIO 2 - PROBLEM ANALYSIS.

Background. This incident was caused by a fire that began in the area of a lavatory at the aft end of a narrow body twin-jet aircraft. Attempts to extinguish the fire were unsuccessful. After an emergency landing, when exits were opened for emergency evacuation, a flashover occurred involving the entire aircraft. The aircraft was destroyed; the crew of five and 18 passengers evacuated safely. Twenty-seven passengers perished.

Detection of the Fire. Initially, the fire in the vicinity of the lavatory was detected by a passenger who smelled smoke. The fire had developed sufficiently to produce discernible smoke and shortly thereafter, had grown enough to make the lavatory door hot to the touch and filled the lavatory with smoke. Obviously detection occurred only after the fire had become well developed. Fourteen minutes before the passenger detected smoke, three circuit breakers on the lavatory flush motor "popped" and would not reset. While it could never be established definitively, these circuit breakers were probably the first available detection clue. The Cockpit Crew treated them, however, as electrical failures and attempted to reset immediately and again after a period of cooling. Neither attempt was successful. The Captain did not order a visual inspection of the lavatory area adjacent to the flush motor.

Localization of the Fire. Smoke was seen in the aft lavatory and it was correctly assumed that the fire was in or communicating with the lavatory. In attacking the fire, the Flight Attendant "saturated the lavatory" even though the prescribed procedure is to apply the extinguishing agent directly at the base of the fire. In this scenario, locating the fire would have required breaking through the lavatory wall. Such aggressive fire attack, however, is not specified for flight crews.

Identification of Fire Severity. Since the fire source was never located, there was no visual estimate of severity. The intensity of the smoke and the heat of the lavatory door led to the conclusion that it was a significant fire. However, an apparent reduction in smoke level reported by a Flight Attendant to the Captain was wrongly interpreted to mean that the severity was reduced. It is very probable that this apparent reduction in smoke was simply the result of closing the lavatory door (after use of an extinguisher) which allowed the cabin air system to dilute the smoke in that area.

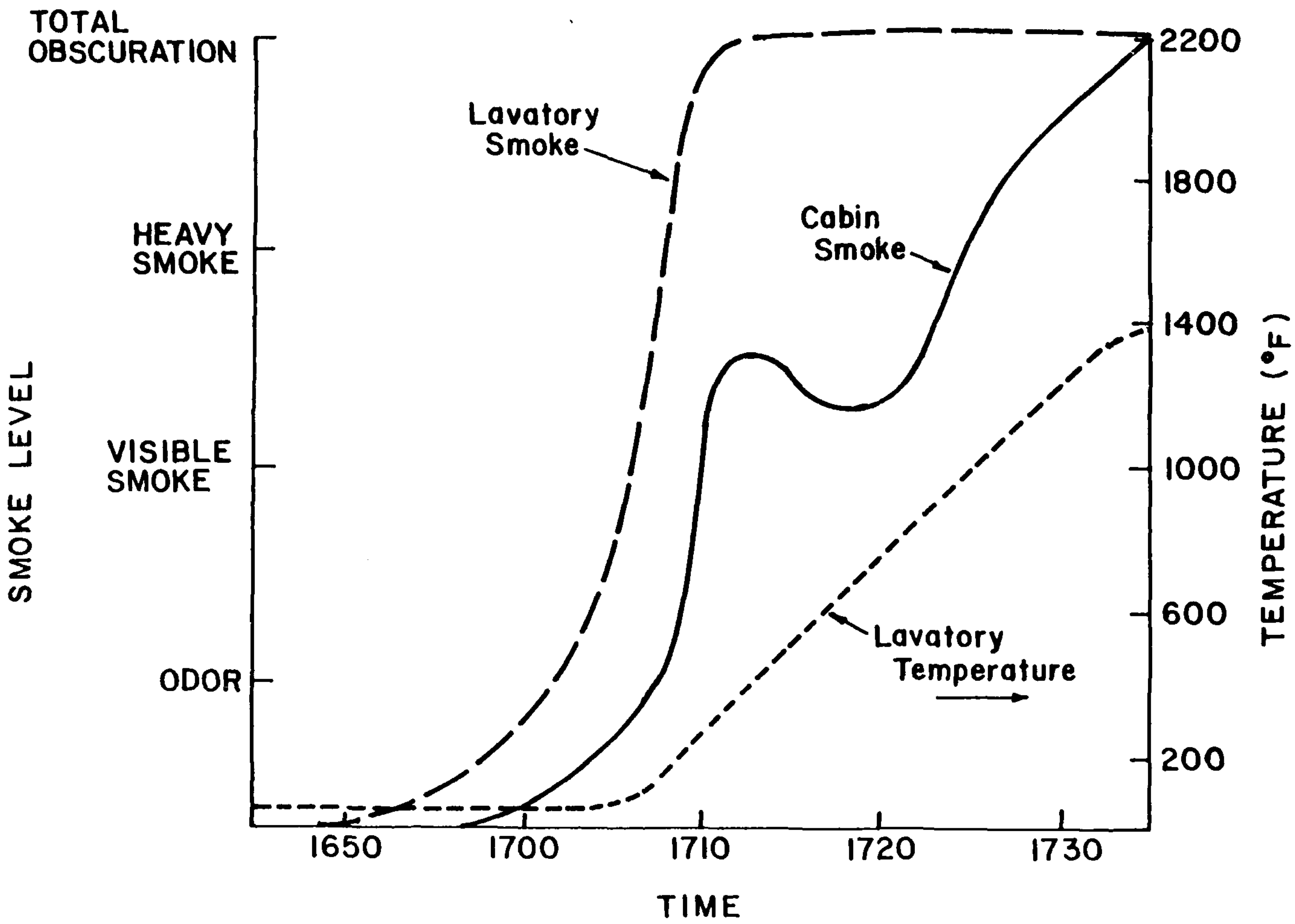

FIGURE 8. SCENARIO 2: SMOKE-TEMPERATURE SIGNATURES

Evaluation of Situation and Choice of Action. The initial evaluation and response using a CO_2 extinguisher was appropriate but it was not properly implemented: the source was never seen and thus the agent could not have been applied to the base of the flame as required for this agent to be effective. The Captain accepted and relied on the observations and reports of the Attendants. He did not interrogate them for more detailed information nor did he direct them to take specific steps to obtain a more definitive picture of severity. The Captain deferred declaring an emergency while he was receiving the reports, and during this interval the fire further increased in intensity.

Conclusions. The Captain did not have a valid assessment of the fire's severity. Further, he did not declare an emergency and divert to an alternate field when he was first made aware of the fire. Had an immediate diversion been made, the flight could have landed between three and seven minutes earlier. That interval might have allowed complete evacuation.

SCENARIO 2 - ACES ANALYSIS. The analysis reported in the fire narrative for this scenario indicates that the fire ignited at about 1649 under the floor of the aft lavatory. Insulation on the wiring of the flush motor was burned through leading to the nearly simultaneous tripping of three circuit breakers (one on each phase of the motor) at 1654. It is estimated that smoke appeared in the lavatory possibly as early as 1652.

Considering first an ACES instrumentation of only the lavatory, it is probable that smoke would have been sensed at no later than 1655 (depending on the location of the sensor and the rate of smoke movement). The ACES would have almost immediately determined a positive, slow rate of rise in smoke intensity. This would place the system in a smoke alert and reset the heat detector redline. At about the same time, however, the circuit breakers had "popped" and ACES would interpret this as circumstantial evidence and would have gone into a positive alarm state denoting the almost certain existence of a fire. Because the origin of the fire was remote from the lavatory and because the burning that did occur in the trash chutes was automatically extinguished, the lavatory temperature signature did not begin to change until about 1708. Recognition of the breaker trips would have allowed ACES to localize the fire to the flush motor area and not the lavatory itself. This would have indicated to the Flight Crew that suppression efforts would likely be ineffective and directed their attention to an immediate diversion. Given initial ACES smoke sensing at 1655, it can be assumed that the positive alarm would have occurred at no later than 1656. Allowing one minute for crew reaction and decision making, i.e., decide to land at nearest suitable field, and a further two minutes for request and receipt of an ATC clearance, this flight could have been in descent toward an alternate at 1659--a full 18 minutes earlier than actually occurred. Further, if the diversion had begun at 1659, Nashville would have been the closest appropriate field and at that time was about 5 minutes flying time from the flight's position. Thus, the flight could have been on the ground at 1704 in contrast to the actual time of 1724. At 1704 the smoke had not penetrated into the passenger compartment, and it is likely that a maximum effort stop and a safe emergency evacuation could have been made of all passengers and crew.

While it is believed that the reaction and response times used above are conservative, the fire narrative suggests that even if the time of touchdown were as late as 1710 a safe evacuation would have been possible. Beyond 1710,

the fire is fully active and growing which greatly reduces the opportunity for complete, safe evacuation. Thus, in this situation the ACES system gives the crew significantly greater time to plan and execute the diversion. As a consequence of this specific flight path, not only is there more time available, but also the flight would have been closer to an appropriate diversion field than was the case in the actual scenario.

A different perspective of the ACES system is afforded by this scenario. This fire occurred in an under-floor space which might be a candidate for instrumentation. In the ACES concept, the selection and location of sensors and detectors will be guided by the relative risk of fire in the various aircraft areas as well as by the potential consequence of fire in these areas. Had the area under the aft lavatory been selected, because of the presence of electrical systems and hydraulic lines as well as proximity to a passenger area, the ACES system would have sensed smoke and heat and determined positive rise rates for both even earlier than would the ACES instrumentation in the lavatory only. The result would have been an earlier alarm even without the information from the tripped circuit breakers. This is not to suggest that this particular under-floor area should be included in any given ACES implementation. It is simply illustrative of the types of considerations needed to reach final design decisions.

TABLE 2. SCENARIO 2 - TIMELINE SUMMARY

ACES BENEFIT	System alarm at 1656. Emergency *declared.*	Begin descent/ diversion at 1659 *Touchdown* at 1704							
ACTUAL RESPONSE	Attempt to reset	Same	Investigate & discharge CO_2 into lavatory	FO returns to cockpit for smoke goggles	Halon system in trash chute activates		No attempt to enter lavatory	Captain concurs	
ACTUAL DETECTION	Circuit breakers "popped"	Same	Passenger detects odor	Smoke too dense to penetrate		Visual by FO and Attendant	Sensory by FO		
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Circuit breakers trip	Circuit breakers do not reset	Odor	Same	Same	Same	Lavatory door hot to touch	Same	Same
COMBUSTION EVIDENCE AVAILABLE	Temper-ature rise on motor	Continued rise	Heat; smoke	Same	Less smoke in cabin	Same	Smoke build-up in lavatory	Smoke; heat	Same
EVENT	Flush motor overheats	Repeat CB reset	Passenger report	FO investi-gates lava-tory	FO suggests emergency *landing*	FO states smoke is *reduced*	FO makes 2nd in-vestiga-tion	FO suggests emergency landing	Emergency declared
TIME	(1654)	(1705)	(1708)	(1710)	(1710:30)	(1711)	(1712)	(1713)	(1716)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Descent	

TABLE 2. SCENARIO 2 - TIMELINE SUMMARY (Continued)

ACES BENEFIT	Landing could have been as early as 1704		
ACTUAL RESPONSE	Begin emer- gency descent	Emer- gency landing	CFR foam/ water
ACTUAL DETECTION			Visual sensory
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Same	Same	Flames, smoke outside aircraft
COMBUSTION EVIDENCE AVAILABLE	Same	Same	Flash fire
EVENT	Begin descent	Touch- down	Emergency evacuation
TIME	(1717)	(1728)	(1730)
FLIGHT PHASE	Descent	Landing	

SCENARIO 3 - RESPONSE TO FALSE ALARM.

SCENARIO 3 - DESCRIPTION. A wide body, four-engine jet aircraft with a flight crew consisting of Captain and First Officer and a cabin crew of 10 Attendants was dispatched from San Francisco to Tokyo via Anchorage. The pre-flight checks were all completed normally. Because of an unusually large amount of bulky, oversize luggage and packages, the aft, bulk baggage compartment was at least half full. The flight departed San Francisco at 1200 and made a normal takeoff, departure and climb. The crew--Flight and Cabin--was experienced, fully qualified for the aircraft and had flown together frequently.

At 1330 a brief intermittent indication of smoke in the lower aft baggage compartment appeared on the fire warning panel and the master warning indicator was activated. The Captain reset the master warning: the smoke indication was momentary and upon being reset remained normal. The Captain and First Officer discussed the implications of the apparently transient indication of smoke. They directed the Senior Flight Attendant to examine the passenger compartment, especially the aft section, for any odor or visible signs of smoke. While this was being done, the Flight Deck crew checked the electrical and warning systems and found all indications normal.

The Captain concluded that the transient indication was a false alarm, the result of equipment malfunction or the presence of vapor or dust which generated a "smoke" indication. He informed the Senior Flight Attendant of the situation and directed that all Attendants be made aware of the occurrence of the false smoke alarm and remain alert for smoke odor and visible smoke.

At 1345 the same compartment smoke indicator again showed a brief, intermittent signal and the master warning indicator was activated. The smoke indicator then turned steady indicating smoke in the compartment. The Captain reset the master warning indicator, directed the First Officer to activate the first fire bottle and then declared an emergency to ATC and requested immediate descent and direct clearance to Seattle-Tacoma International. At this time, the flight was 875 miles en route from San Francisco, 1200 miles from Anchorage and 475 miles WNW of Seattle-Tacoma, which was the closest suitable airport with acceptable weather. Diversion to Seattle-Tacoma was estimated to take 50 minutes.

Following company procedures, the Captain set the cabin altitude to 10,000 feet, set pack 1 to maximum on and placed the equipment cooling valve control switch at SMOKE. He donned his oxygen mask and selected 100%. He summoned the Senior Flight Attendant for a briefing on preparations for emergency landing. The First Officer also donned his oxygen mask at 100%. ATC cleared the flight direct to Seattle and gave approval for an immediate emergency descent. A weather briefing was issued, all controlled traffic was notified of the emergency and diverted as required. Emergency services were alerted at Seattle-Tacoma and aircraft rescue and fire fighting (ARFF) equipment was dispatched to the landing runway and adjacent taxiways.

At 1420 the flight entered Seattle-Tacoma Approach Control and final clearance was given for a straight-in approach. The Captain planned to execute a maximum effort stop after landing. Over the intercom, the Captain directed the Flight Attendants to review with the passengers the procedure for evacuation at the conclusion of the landing roll. The Seattle-Tacoma tower saw evidence of

smoke as the aircraft was on final, and the Captain confirmed a maximum effort stop and emergency passenger evacuation. Touchdown was at 1438 and the aircraft stopped in two-thirds of the runway. All emergency evacuation slides were successfully deployed. Passengers and crew safely exited the aircraft with only minor injuries; the passengers were directed away from the aircraft by emergency personnel and the fire crew opened all baggage compartments and entered the passenger compartment. No evidence of smoke or fire was discovered. An inspection panel in the area of the baggage compartment was only partially fastened.

Subsequent investigation indicated that the smoke detector had malfunctioned because of a connector failure which allowed a short to ground to occur. The "smoke" evidence seen by the tower was, in fact, dust and water vapor which apparently issued from the partially opened inspection panel.

SCENARIO 3 - FIRE NARRATIVE. This incident resulted in a false alarm and no actual fire. Therefore, a fire narrative is not included.

SCENARIO 3 - PROBLEM ANALYSIS.

Background. The flight in which this incident occurred had been airborne for one and one-half hours and was approximately three hours from its next intermediate stop. An intermittent smoke alarm was judged to be false but a subsequent steady-state alarm was accepted as a true indication and emergency landing procedures were initiated. All appropriate emergency procedures including use of an extinguishing system and passenger evacuation were followed. Ultimately, the alarm proved to be false.

Detection of the Fire. In this incident, detection was made through a smoke sensor located in the aft baggage compartment. An initial intermittent indication was interpreted as a false alarm but later when the alarm went to a steady state it was considered a true alarm. Detection was accomplished quickly and correctly, i.e., the alarm was accepted as evidence of smoke in the compartment. No smoke odor or visible smoke was detected. No second sensor converted by "AND" logic was available for verification.

Localization of the Fire. Localization was not an issue in this incident because the alarm itself indicated the location: the aft baggage compartment.

Identification of Fire Severity. The Captain in this incident is not required to assess severity because his only response option is to activate the extinguisher system, declare an emergency and proceed to the nearest alternate airfield: all of which were done. Had the Captain (for whatever reason) judged the severity to be tolerable for continuation of the flight, he might have simply continued to the intermediate stop. He might have, for example, assumed that the Class D status of the compartment ensured containment of the fire and the integrity of the aircraft. Such a decision, however, would be in direct violation of the specified procedures and would not be logical in this situation where there was a relatively long flight to the intermediate stop.

Evaluation of Situation and Choice of Action. This process was a routine response in this situation. The immediate diversion and activation of the extinguishing system was the only possible response and, further, it was mandated by the company's emergency procedures. Also, the declaration of an

emergency, and the decision to make a maximum effort stop and evacuate the passengers were fully warranted by the evidence of the smoke alarm substantiated by the tower's incorrect determination that smoke was issuing from the aircraft during landing.

Conclusion. This incident was handled in exact conformance with specified procedures. Had the first indication of alarm been accepted as true, the Captain would have declared an emergency about 15 minutes earlier than he did. If there had been a fire, this interval might have been significant for extinguishment. In this incident, that delay was not important. The maximum effort stop and slide evacuation might not have been employed if the dust and water vapor had been correctly identified and not presumed to be smoke.

SCENARIO 3 - ACES ANALYSIS. This scenario depicts a false alarm to which the crew made a complete emergency response. The ACES system would have determined the first, intermittent, signals from the sensor to be false because the signal would have stepped instantaneously from zero, i.e., no smoke, to redline level. Any real fire or smoke incident would have built up to the redline in a ramp function. The ramp may have been steep, but the change would not have been instantaneous in the shape of a square wave.

At the same time that the ACES system would have informed the cockpit that there was a system malfunction, it would have reset the redline limits on the associated heat detector. It would also have reset the limits on both heat and smoke detectors in adjacent areas. The failed sensor would have been "placarded" by ACES and removed from the system.

Meanwhile in addition to identifying the step function, the ACES system would have evaluated the heat detector paired with the malfunctioning smoke detector as well as the relevant circumstantial indications. Again the conclusion would have been that the alarm was false.

The benefit of ACES in this situation is that the flight could have continued normally. Even if the Crew elected (or was compelled by policy or regulation) to divert because of a malfunction in the ACES, the assurance that the alarm was false would allow them to be more selective as to a diversion field. Normal flight landing and deplaning procedures would also be followed thereby avoiding the minor injuries associated with the emergency evacuation.

TABLE 3. SCENARIO 3 - TIMELINE SUMMARY

ACES BENEFIT	Display sensor/system malfunction, log on BITE			Flight continues on to planned destination	
ACTUAL RESPONSE	Conduct manual inspection	Treat as false	Divert; monitor fire, counter-measures (Halon, etc.)	Choose emergency landing and evacuation	Minor injuries
ACTUAL DETECTION	Cockpit warning		Same	Same	
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Step rise in sensed smoke		Step rise in sensed smoke	No variation in sensed smoke level	
COMBUSTION EVIDENCE AVAILABLE					
EVENT	1st intermittent activation of smoke sensor	Examination of plane by crew	Steady activation of smoke sensor	Approach to diversion airport	Emergency stop and evacuation
TIME	(1330)	(1335)	(1345)	(1420)	(1438)
FLIGHT PHASE	Cruise	Cruise	Cruise	Approach	Landing

SCENARIO 4 - FALSE ALARM.

SCENARIO 4 - DESCRIPTION. A narrow body tri-jet aircraft was at Flight Level 240 en route from Little Rock, Arkansas to St. Louis, Missouri. Takeoff and climb to en route altitude were normal. There were 60 passengers on board (the aircraft was configured for 142 passengers - single class). At 1340, 30 minutes after takeoff, the flight was 150 miles north of Little Rock and about 200 miles from Lambert St. Louis International Airport, its destination; it was about 60 miles west of Poplar Bluff (Earl Fields Memorial Airport). At this time, the smoke detector indicator for the aft lavatory activated along with the master warning indicator. The Captain reset the master warning and directed a Flight Attendant to investigate. He also dispatched the First Officer to the scene in accordance with company procedures. The First Officer took his smoke mask and oxygen bottle and was advised by the Captain to make a prompt assessment and report back to the flight deck on the intensity and quantity of smoke, the source--if identifiable--and the potential for controlling the source. This procedure is specified in the company manual. A hand-held Halon extinguisher is mounted on the bulkhead behind the last passenger seat on the right side. The First Officer would use this extinguisher to attack the fire. At 1343 the First Officer was at the scene.

Upon arrival at the lavatory, neither the Flight Attendant nor the First Officer was able to detect any smoke. There was no odor of burning. The First Officer reported this condition to the Captain who directed that a further search be made. A thorough examination of the entire lavatory was then made and no signs of smoke, fire or excessive heat were found. At 1348, the First Officer and the Flight Attendant completed their search and concluded that the detector signal was a false alarm. The First Officer reported to the Captain that the search was ended. The Captain directed the Flight Attendant to placard the lavatory out of operation and to continue to monitor for any indications of smoke or fire throughout the remainder of the flight. The First Officer returned to the Flight Deck at 1351. The Captain reported the incident on company radio and requested maintenance to be available upon arrival. The flight continued without further incident and landed at St. Louis at 1425.

It was subsequently determined by maintenance that the smoke detector had malfunctioned, and it was replaced.

SCENARIO 4 - FIRE NARRATIVE. This incident was the result of a smoke sensor malfunction and no actual fire. Therefore, a fire narrative is not included.

SCENARIO 4 - PROBLEM ANALYSIS.

Background. This false-alarm incident took place 30 minutes after takeoff on a short flight when the aircraft was over an area in which many alternate airfields were readily accessible.

Detection of the Fire. Detection occurred when a smoke alarm was activated in the cockpit. Detection was immediate and the alarm was accepted as evidence of a fire.

Localization of the Fire. Localization was simultaneous with the alarm because the sensor is located in the aft lavatory. More exact localization was not required since the alarm proved false.

Identification of Fire Severity. By means of direct examination of the aft lavatory (by both an Attendant and the First Officer) it was determined that there was no fire. This was done correctly and quickly.

Evaluation of Situation and Selection of Action. The Captain selected an appropriate response action by directing the First Officer to assess the situation and prepare to use a hand-held extinguisher. This was done immediately upon the receipt of the smoke alarm and thus was timely. Upon discovery that there was not a fire, the Captain ordered that close surveillance be maintained in the vicinity of the lavatory. He requested the company to have maintenance available at the destination and continued the flight. All of the response actions were appropriate and properly executed.

Conclusions. Even though the alarm proved false, the Captain properly initiated a response that could have extinguished or at least contained a fire in the lavatory. He thus took the steps needed to keep the fire (had it existed) from invading the passenger compartment or at least slowing its invasion. Subsequent actions could have proceeded--if needed--while the fire was being fought. Overall, the scenario depicts prompt, correct emergency responses.

SCENARIO 4 - ACES ANALYSIS. In this scenario a lavatory smoke detector signals an alarm; the crew examines the area and determines it to be free of any fire or smoke condition. An ACES system would have determined that the smoke detector had malfunctioned by determining that the signal was a discrete step function and not a ramp as would be the case in a real fire/smoke event. The ACES would have also determined no heat above ambient and no circumstantial evidence. For this scenario the ACES benefit is primarily that of confidence in the conclusion. There would have been only minimal time savings from an ACES system determination. This scenario did involve a two-person flight crew and the First Officer was directed to leave the cockpit to examine the lavatory area. It is easy to think of situations in which both pilots should stay in the cockpit. The ACES would have allowed that.

TABLE 4. SCENARIO 4 - TIMELINE SUMMARY

ACES BENEFIT	Display sensor/system malfunction, log on BITE		Crew confidence, continue normal flight
ACTUAL RESPONSE	Conduct manual inspect- ion	Decision that alarm was false	
ACTUAL DETECTION	Cockpit warning	Visual	
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Steep rise in sensed "smoke"	Same	Same
COMBUSTION EVIDENCE AVAILABLE			
EVENT	Warning sounds	Manual inspection	Decide to ignore
TIME	(1340)	(1343)	(1351)
FLIGHT PHASE	Cruise	Cruise	Cruise

SCENARIO 5 - LAVATORY FIRE - EXTINGUISHED.

SCENARIO 5 - DESCRIPTION. A wide body tri-jet aircraft with a flight crew consisting of Captain and First Officer and a cabin crew of 12 Attendants, was dispatched non-stop from San Francisco to JFK. Takeoff was at 2200 Pacific time; estimated time en route 5 hours, 15 minutes. The Flight Deck Crew and Flight Attendants were all fully certified and type-qualified. Pre-Flight Checklist and Before-Takeoff Checklist were completed. There were 250 passengers on board. Takeoff and departure were normal and climb to Flight Level 330 was initiated en route to Salt Lake (first waypoint). Cheyenne was the second point. At 2400 (Pacific Time) the flight cleared Cheyenne en route to Omaha.

At 0015 a Flight Attendant in the aft cabin detected a smoky odor and, upon inspection of the lavatories, discovered smoke issuing from the amenities counter of the center lavatory. The Flight Attendant immediately notified the Captain. The smoke indicator and master warning indicator had activated at the time of the Flight Attendant's call. The Captain directed the First Officer to go aft (taking smoke mask and oxygen bottle) to direct the attack on the fire; he ordered the Flight Attendant to use a hand-held extinguisher. The Captain then donned his oxygen mask, selected 100% and proceeded through the cabin smoke/fire procedures: pack flow control latched in; altitude set selector, 10,000 feet; normal rate selector, full increase; and forward outflow valve moved manually toward closed. The First Officer reported to the Captain from the back of the aircraft that extinguishers were being used and that the fire appeared to be controllable. The Captain declared an emergency to ATC and reported on company radio. At 0021 he requested weather and facilities information on Omaha and Kansas City as diversion fields.

The First Officer returned to the flight deck at this time and reported that the fire had been contained and was now being completely extinguished by the Attendants. The Captain advised the passengers of the emergency and reassured them that the fire had been extinguished but that the flight would be diverted.

The weather in the area was being generated by a cold front: the flight was above a solid layer of stratus at about 10,000 feet with broken stratocumulus below that. A line of towering cumulus extended along the north-south frontal face. This line was east of the flight's location about 180 miles and was roughly perpendicular to the flight path. It was estimated that the front would be in the Omaha area at approximately 0400 and the associated thunderstorms would be of severe intensity, visibility would be restricted to less than 1/4 mile in rain. Kansas City reported a similar forecast.

The flight was estimating one hour to Omaha or one and one-quarter hours to Kansas City plus additional time as needed to vector through the front.

At 0032 a Flight Attendant reported that a second extinguisher had been expended and that there were no visible signs or odor of active burning. No visible smoke was present and only the odor of the extinguished residue remained. The Captain directed that only the two outboard lavatories were to be used and that one Flight Attendant was to remain in the area to enforce that and to prevent passengers from gathering in the aft compartment. The Captain informed the passengers of these conditions.

At 0035 the Captain elected Kansas City for diversion. Clearance was granted for a direct, straight-in approach, all controlled aircraft were informed of the emergency and were diverted as required. Emergency facilities at Kansas City were notified and deployed to the taxiways adjacent to the landing runway in accordance with the field's emergency procedure.

At 0050, after confirming that there were no further signs of active fire or smoke, the Captain declined to make a maximum effort stop landing.

At 0115 the Before-Landing Checklist was completed normally. Normal approach and landing were accomplished. Emergency equipment and crews followed the aircraft to the gate where passengers and crew exited the aircraft via the normal exit ways.

Subsequent investigation suggested that a lighted cigarette had been dropped, or rolled from the built-in ash tray, into paper products stored in the amenities counter.

SCENARIO 5 - FIRE NARRATIVE. This fire incident was probably the result of a passenger leaving a lighted cigarette in the ash tray on the amenities counter in the lavatory. Smoke was produced as a result of paper material in contact with the smoldering cigarette after it rolled into a storage bin. This incident did not escalate to the flaming stage since it was quickly extinguished. No diagram is presented because detection was rapid and accomplished both manually and automatically.

SCENARIO 5 - PROBLEM ANALYSIS.

Background. This incident occurred about mid-way in an eastbound transcontinental flight. A Flight Attendant and the lavatory smoke detector detected smoke at the same time. The fire had not developed into a large one and was extinguished by the crew. The flight diverted safely to an alternate air field.

Detection of the Fire. The presence of smoke was detected at the same time by a Flight Attendant and by the lavatory smoke detection system. The detection was positive and was made quickly.

Localization of the Fire. Since the detection was by an automatic system, the location was established within the lavatory. The Attendant's visual inspection located it more precisely as being in the amenities counter.

Identification of Fire Severity. There was no explicit analysis made of the severity. The crew attacked the fire successfully and without injury so it can be inferred that they correctly judged the fire to be controllable.

Evaluation of Situation and Selection of Action. The situation was immediately and correctly evaluated and the extinguishing action was successful. The decision to divert to and land at the closest appropriate airfield was made in a timely way and executed according to specified procedures. No emergency evacuation was ordered because the fire was successfully extinguished.

Conclusions. This incident was dealt with and in keeping with specified procedures and the fire was successfully extinguished while an appropriate emergency diversion was being accomplished.

SCENARIO 5 - ACES ANALYSIS. In this scenario a lavatory fire is detected, emergency procedures are initiated and the fire is extinguished while inflight. The flight was diverted to the nearest appropriate field. The ACES system would likely have detected this incident earlier than the human and existing sensor detection that actually took place. The ACES logic would have been applied: sensing of smoke, determination of a positive rate of rise in smoke, and a forecast of exceeding the redline. Since the fire had not developed beyond a state that was controllable by hand-held extinguishers, it was apparently not active or rapidly developing. The few minutes more time that an ACES would have provided would not have materially changed this situation. It must be noted that in-flight fire suppression can at best be considered a holding action while the flight is being diverted and put on the ground as quickly as possible. This lavatory fire (as any in-flight fire) could have grown beyond the capability of the available hand-held extinguishers. Early, positive, alarms always provide more time for planning and executing an emergency diversion as well as time for direct attack on the fire. The ACES would therefore have provided an added margin of time which would have been an additional safety factor.

TABLE 5. SCENARIO 5 - TIMELINE SUMMARY

ACES BENEFIT	System alarm prior to 0015		Outcome basically the same		
ACTUAL RESPONSE	Alert cockpit	Manual firefighting; prepare for diversion	Monitor and fight fire; declare emergency	Conclude fire out; divert to Kansas City	Complete normal landing and passenger exit
ACTUAL DETECTION	Olfactory/ visual	Smoke sensor	Same	Olfactory/ visual	Manual monitoring
CIRCUMSTANTIAL EVIDENCE AVAILABLE		Attendant verification	Attendant & First Officer verification	Attendant verification	Successful firefighting and monitoring
COMBUSTION EVIDENCE AVAILABLE	Smoke; small heat rise	Smoke; small heat rise	Smoke; small heat rise	Greatly reduced particulate; heat back to ambient or below	
EVENT	Attendant detects smoke	Cockpit warning activated	Received diversion information	Completion of firefighting	Normal landing
TIME	(0015)	(0015)	(0021)	(0032)	(0119)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	

SCENARIO 6 - LIGHTING BALLAST OVERHEAT.

SCENARIO 6 - DESCRIPTION. A wide body four-engine jet aircraft was en route San Francisco to New York at Flight Level 370. Local time was 2030; meal service had just been completed and the cabin prepared for the remainder of the flight. The flight was on time and on the filed flight plan. The outboard cabin overhead lights were on; the aisle overhead lights were dimmed. At 2035 a passenger reported to a Flight Attendant that he smelled the odor of overheating electrical equipment. That Attendant then directed a second Attendant to notify the flight deck and began to search for the source of the odor. It was strongest in the area of Row 12, just ahead of the passenger who had reported an odor. There was no visible smoke and no part of the overhead or wall lining was hot to the touch. She then went to the Flight Attendants' Panel (at 2039) and turned off the section of overhead lights in the area of Row 12. She reported her observation and action to the Captain who directed the Flight Engineer to pull the related circuit breaker. The Captain also directed that the flow rate of cabin air be increased. The Flight Attendant was told to keep the area of Row 12 under surveillance and keep the flight deck informed. The flight continued without another incident. Maintenance at New York removed and replaced the defective ballast and the aircraft was returned to service.

SCENARIO 6 - FIRE NARRATIVE. This incident resulted in overheating electrical equipment, however, no actual fire started.

SCENARIO 6 - PROBLEM ANALYSIS.

Background. This incident involved a defective lighting ballast which overheated, giving off a burning odor. The situation was quickly detected and appropriate action was taken.

Detection of the Fire. In this incident there was no actual fire. The overheated ballast was detected, by odor, apparently very soon after it had begun to overheat.

Localization of the Fire. The location of the ballast was quickly and easily determined by the Attendant and the passenger.

Identification of Fire Severity. The Attendant correctly determined that the source was an overheating ballast and that its severity was not significant.

Evaluation of the Situation and Selection of Action. The overheating problem was correctly assessed as non-significant provided that the power was shut off. This was done and the problem was effectively resolved.

Conclusions. This incident was correctly and efficiently handled. Power was shut off at the Attendant's panel and subsequently the related breaker was pulled: a redundant shut-down which ensured that power would not easily be reapplied.

SCENARIO 6 - ACES ANALYSIS. This incident involved an overheated lighting ballast. The ACES system in its most basic concept would not be involved in such an incident. The failure would be detectable by other means as in the scenario when a passenger detected the odor. A more elaborately structured ACES could possibly have detected heat and/or particulate in the "attic" area of the aircraft and might have detected current changes from the data bus. Any benefit, however, from detecting the incident slightly earlier can at best be deemed marginal.

TABLE 6. SCENARIO 6 - TIMELINE SUMMARY

ACES BENEFIT	System probably not involved	
ACTUAL RESPONSE	Visual inspection	Turn off power
ACTUAL DETECTION	Passenger detects odor	Attendant localizes source
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Odor	Same
COMBUSTION EVIDENCE AVAILABLE	Localized heat	Same
EVENT	Passenger report	Power off
TIME	(2035)	(2039)
FLIGHT PHASE	Cruise	Cruise

SCENARIO 7 - AVIONICS COMPARTMENT SMOKE.

SCENARIO 7 - DESCRIPTION. On a flight from Newark International to Dallas-Fort Worth, a narrow body twin-jet aircraft was dispatched from the gate at 1328 local time. There were 120 passengers on board and a crew of seven (Captain, First Officer and 5 Flight Attendants). The flight was airborne at 1339 and vectored to en route air traffic control at 1350 at flight level 250, climbing between Allentown and Philadelphia. Upon reaching flight level 310 at 1358, all checklists had been completed; meal service including a hot sandwich choice was initiated.

The flight proceeded routinely with no deviation from the flight plan and no unusual events or indications. Just prior to 1530 when the flight was approaching the Nashville area, the First Officer reported the odor of overheating electrical equipment. The Captain and First Officer scanned all operational, status and warning indicators and found no abnormal indications. At 1530 the avionics smoke detector alarmed and the master warning was activated. At 1531 smoke appeared on the flight deck apparently rising from below the floor at the aft end of the cockpit. The flight deck crew donned oxygen masks and smoke goggles and went on 100% oxygen. The master warning was reset and all other cockpit indicators/displays were again reviewed and no abnormal indications were noted. The smoke had increased in density. At 1532, the First Officer located the Checklist for Electrical Fire and Smoke and with the Captain completed the checklist. The Captain called the Flight Attendant in-charge and inquired if smoke was visible or could be smelled in the cabin and was told, not at the moment. He advised the cabin crew not to open the cockpit door. At 1533 the intensity of the smoke continued increasing slowly. The Captain initiated the Smoke Removal Checklist. The increased ventilation removed smoke although it appeared that the source of smoke had not been affected by turning the utility bus switches off. The Flight Attendants reported that smoke had become apparent in the cabin, the odor had been detected but no visible signs were present.

At 1534 the Captain declared an emergency to ATC and requested immediate direct clearance to Nashville, which was designated on the Flight Management System (FMS) display as an appropriate diversion field. He directed the First Officer to shut down all avionics/communication equipment not needed for an emergency approach and landing. The First Officer located the printed electrical equipment abnormal shut-down procedure and initiated it. ATC vectored the flight through a manually-controlled descent to the Nashville area. The smoke on the flight deck continued to be heavy and visibility was reduced but the instrument panel was visible and adequate outside visibility was maintained. At 1538 having reached 3000 feet, the Captain reduced power to minimum air speed and directed the First Officer to open his side window to evacuate smoke. The smoke began to dissipate. The First Officer confirmed that full rate cabin air exchange was operating. He inquired as to cabin conditions and the Chief Flight Attendant reported that the odor of smoke was detectable and smoke had become visible in the area of the flight deck. She requested and was granted permission to move all passengers aft.

At 1540 ATC handed the flight over to the Nashville tower which confirmed radar contact. The Captain directed the cabin crew to brief the passengers on maximum effort stop after landing and emergency evacuation. Smoke in the cockpit had diminished but there appeared to be a persistent source of at least

moderate smoke. The First Officer had opened a cockpit window but closed it periodically because of the noise which interfered with voice communication. At 1542 the flight began a straight-in final approach. Nashville tower confirmed visual contact and notified the flight that AFRR vehicles had been deployed to the landing runway area. Touchdown was at 1544. At 1546 the Emergency Engine Shut-Down Checklist was completed and emergency evacuation slides were deployed. All passengers and crew exited the flight with only minor injuries.

The avionics bay was accessed by fire-fighting personnel who found charred insulation (with slight residual smoking) related to one of the navigation computers.

SCENARIO 7 - FIRE NARRATIVE. At approximately 1527 an unknown electrical malfunction resulted in the overheating of a wire in the circuit of one of the navigation computers. Smoke from the overheated wire accumulated within the equipment cabinet and spread to the avionics bay (Figure 9A). The temperature within the avionics bay stayed relatively constant, since the limited heat produced by the overheated wire remained localized within the navigational computer. At 1530 the First Officer detected the odor of overheating electrical equipment and a minute later he detected visible smoke on the Flight Deck. Also at 1530 the smoke detector located at the ceiling in the avionics bay sounded an alarm. At this point, conditions of marginal visibility existed in the avionics bay and the smoke continued to accumulate in the cockpit (Figure 9B). At 1533 the odor of smoke was detected in the passenger cabin and marginal visibility (heavy smoke, but instrument panel still visible) was reached in the cockpit (Figure 9C). Conditions deteriorated in the avionics bay to nearly total obscuration. At 1540 smoke continued to accumulate on the flight deck despite intermittent opening of the First Officer's window to ventilate smoke. At 1544 the aircraft touched down and after a maximum effort stop and passenger evacuation only residual smoke remained. The smoke signatures are shown in Figure 10.

SCENARIO 7 - PROBLEM ANALYSIS.

Background. This incident involved electrical/electronic equipment overheat; it is likely that no open flame was involved although a large amount of smoke was generated. The flight was a relatively short one and the incident occurred about midway to the destination when the flight was over an area in which several alternate airfields were available. The incident was handled effectively.

Detection of the Fire. Initial detection in this incident was by the odor of smoke in the cockpit and then by a compartment smoke detector and the appearance of smoke on the flight deck almost simultaneously. Detection most likely occurred very soon after the overheat began to produce smoke.

Localization of the Fire. Because it was detected by a compartment sensor, the location of the incident was known immediately. More exact location within the compartment would have required opening the hatch to the avionics bay which would have taken time and disrupted passengers and crew.

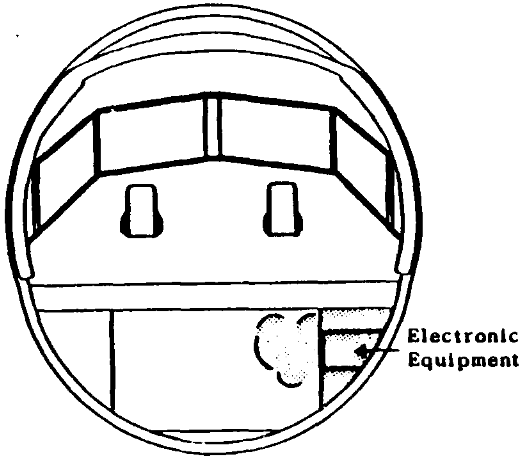

FIGURE 9A. SMOKE ACCUMULATES IN EQUIPMENT CABINET

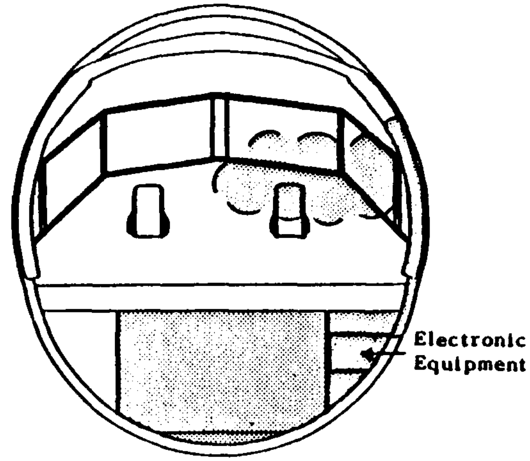

FIGURE 9B. SMOKE ACCUMULATING IN COCKPIT

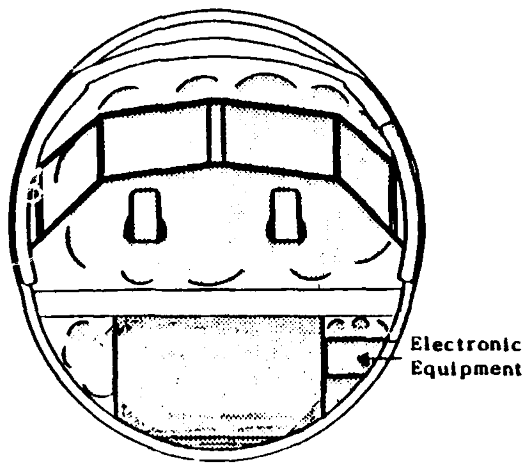

FIGURE 9C. SMOKE IS HEAVY IN COCKPIT, FILLS AVIONICS BAY

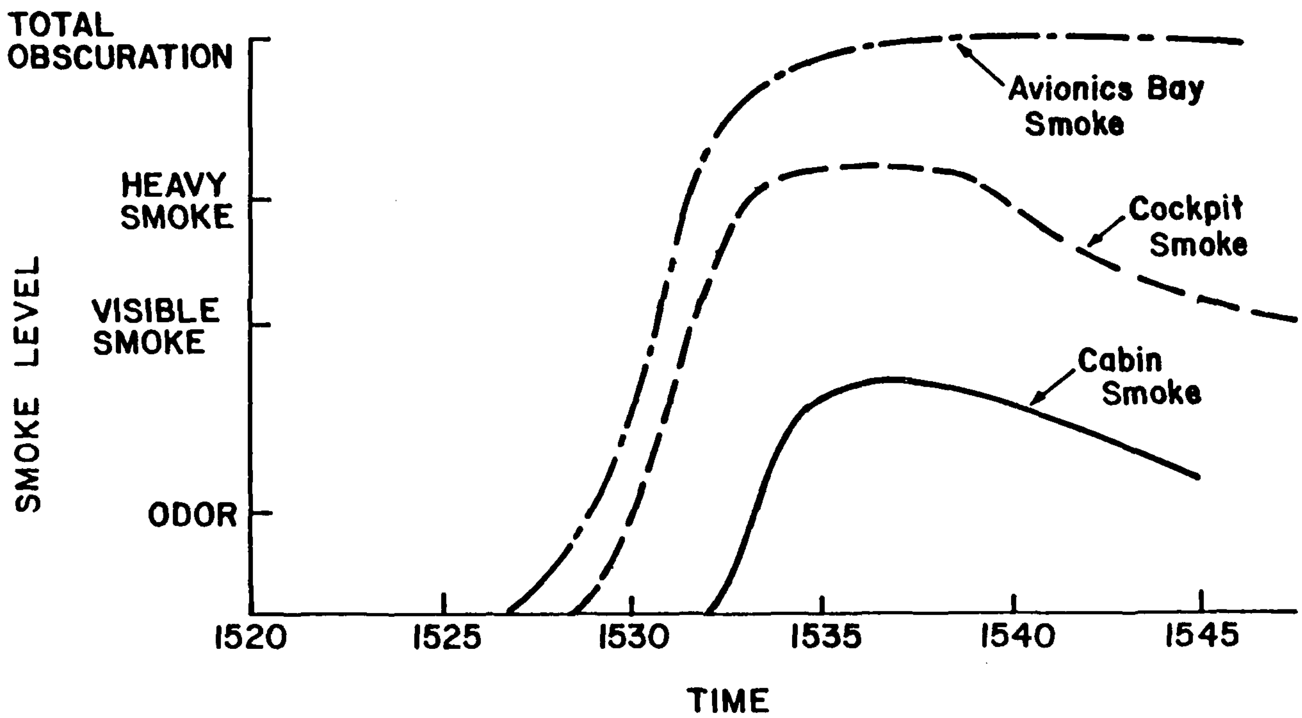

FIGURE 10. SCENARIO 7: SMOKE SIGNATURES

Identification of Fire Severity. Severity of this incident was assessed indirectly by systematically removing loads on the electrical system. Turning the utility buses off did not noticeably reduce the apparent smoke. Therefore the Captain ordered all electrical equipment turned off except for the equipment absolutely necessary for emergency approach and landing. This did result in a reduction of the quantity of smoke.

Evaluation of the Situation and Selection of Action. The Captain's evaluation was that the alarm and the presence of smoke indicated a severity warranting an emergency landing. The Captain initiated specified procedures including use of oxygen, goggles, equipment shutdown and diversion to closest appropriate airfield. All of this was done correctly and in a timely way.

Conclusions. This incident was handled according to specified procedures and all responses were made promptly and correctly. Because the avionics bay is not readily accessible in flight, precise and selective equipment shutdown was not possible.

SCENARIO 7 - ACES ANALYSIS. In this scenario, smoke was generated by overheating of avionics equipment in a compartment under the flight deck. The overheating was localized and not sufficient to "pop" a circuit breaker. This is an unusual scenario in that load shedding did not reduce the overheating. Also, no active burning developed--even though the overheating persisted. It is, however, not a wholly improbable scenario: the affected equipment was apparently critical and thus not shut down in load shedding. The heat production had apparently stabilized at a level just below the breaker threshold.

In this situation, the ACES system would have sensed smoke at about 1527. Almost immediately, a positive rate of rise in smoke would have been determined but little heat change would have been sensed. The ACES system would then have indicated a smoke alert condition, reset the heat redlines and continued to monitor for circumstantial evidence. At about 1528 the ACES would have determined a growing rate of rise in smoke and denoted a smoke alarm condition.

Given the earlier alert in the ACES system, the crew could have initiated smoke removal procedures earlier and perhaps have reduced the amount of smoke in the cockpit. In addition to quicker alerting, the ACES would have provided more efficient access to the appropriate emergency procedures. There are no other direct benefits from the ACES system in this particular scenario.

TABLE 7. SCENARIO 7 - TIMELINE SUMMARY

ACES BENEFIT	System alarm at 1528			Earlier smoke removal by crew		More efficient access to appropriate emergency procedures		
ACTUAL RESPONSE	Search for abnormal indication	Locate checklist	Same	Initiate electrical fire/ smoke checklist	Initiate cockpit smoke removal	Start descent	Evacuate smoke through window	Emergency evacuation
ACTUAL DETECTION	FO detects odor	Visible/ audible alarm	FO detects visible smoke					
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Odor		Odor	Same	Same	Same	Same	
COMBUSTION EVIDENCE AVAILABLE	Smoke; heat	Smoke	Same	Increasing smoke	Decreasing smoke	Same	Same	
EVENT	FO detects odor	Avionics smoke alarm activates	Smoke in cockpit	Initiates checklist electrical fire	Initiate smoke removal	Declares emergency	Cockpit window open	Touchdown
TIME	(1529)	(1530)	(1531)	(1532)	(1533)	(1534)	(1538)	(1544)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Descent	Landing

SCENARIO 8 - CONCEALED FIRE (CLOSET).

SCENARIO 8 - DESCRIPTION. On a flight from Miami International to New York, JFK, a wide body twin-jet aircraft was dispatched from the gate at 2230. All pre-flight inspections and checklists showed everything to be normal and the Pre-Takeoff Checklist was initiated while taxiing to the runway. The Pre-Takeoff Checklist was completed with no deviations and the flight was airborne at 2242.

The flight was in a single-class configuration and carried a full load of 230 passengers during the heavy traffic period at the end of the winter season. The crew consisted of Captain, First Officer and 8 Attendants. There was an unusually large amount of carry-on luggage and clothing. The overhead bins and all of the clothes closets were filled. The folding closet doors were secured during flight and normally would not be opened until after landing. The flight proceeded normally for the first half of the scheduled three-hour trip. A drink and snack service had been completed and there was little or no passenger movement in the cabin. At 0012 a passenger in the first row, right side detected the odor of smoke and notified a Flight Attendant. The Attendant observed a light flow of smoke issuing from the top of the door to the closet forward of the passenger seating area on the left side of the aircraft. This closet is adjacent to the front, left passenger entrance and opposite the forward lavatory. At this location, a cross aisle is formed between the passenger entrance and the service accessway on the right side of the aircraft.

The Attendant opened the closet door only enough to see that the closet was filled with whitish smoke having an acrid odor--a large amount of smoke spilled into the cabin. The Attendant closed the closet and went into the cockpit to inform the Captain at 0013. The Captain called the Senior Flight Attendant forward and directed that an extinguisher be discharged into the closet. He also directed that the curtain between the passenger seats and the closet/lavatory area be closed. One Attendant was directed to remain at the cockpit area for communication; one was directed to attempt to determine the exact location and extent of the fire within the closet. Two Attendants were directed to remain in the passenger area to reassure and help the passengers. The first extinguisher was discharged at 0014.

The Captain and First Officer consulted briefly and decided to declare an emergency which the Captain announced to ATC at 0017. The Captain and First Officer donned smoke goggles and oxygen masks at 100% oxygen, the Attendant at the cockpit door donned a smoke mask and a portable oxygen bottle. Additional fire extinguishers were brought forward and the Attendant at the closet began removing the contents and used a second extinguisher at about 0018. The Attendant reported that there was no visible flame and that the smoke was heavy but that it appeared not to be increasing. Meanwhile, the Captain had initiated an emergency descent and the flight was passing through Flight Level 270. ATC granted clearance direct Raleigh-Durham at 0019 which, at that time, was approximately 70 miles, on-course. Clearance was given for an emergency approach; all affected traffic was notified and Raleigh-Durham began to deploy ARFF vehicles to the landing runway.

The passengers were attempting to move away from the smoke in the front end and the Attendants in the cabin were busy trying to keep the passengers calm and orderly.

At 0020, descending through 14,000 feet, the Captain directed the First Officer to depressurize the aircraft and confirm that the outflow valves were fully opened. Passengers were directed back to their seats with seat belts fastened.

At 10,000 feet the Senior Attendant informed the Captain that there was no visible fire. At 0022 the Captain initiated and directed the Cabin Smoke Evacuation Procedure. Substantial clearing of smoke was achieved and no visible fire was detected.

The flight touched down at 0029 and a maximum effort stop was made. Emergency evacuation chutes were deployed and all passengers and crew safely exited the aircraft at 0034. There were only minor injuries, but at least half of the passengers were given some treatment for smoke inhalation.

SCENARIO 8 - FIRE NARRATIVE. At approximately 0008 a smoldering fire of undetermined origin began in the carry-on luggage in the forward left clothes closet (Figure 11A). As the smoke accumulated in the closet, it leaked out of the top of the folding door and mixed with the circulating air in the passenger compartment and became somewhat diluted (Figure 11B). At 0012 a passenger detected the smoke odor and notified a Flight Attendant. A large amount of smoke spilled into the cabin when the Flight Attendant opened and closed the closet door during her investigation (Figure 11C). The temperature within the closet had risen only slightly above ambient to about 90°F. At 0014 the Flight Attendant again opened the closet door and discharged a fire extinguisher into the stacked luggage and closed the door. By 0015 the temperature within the closet reached approximately 100°-150° at the ceiling. At approximately 0017, the Attendant again opened the closet door and after removing some of the clothes and luggage, discharged a second fire extinguisher and reported no visible flame. However, smoke was still heavy. By 0019 smoke in the forward end of the passenger cabin was heavy. At 0020 the First Officer initiated smoke evacuation procedures by opening the outflow valves followed by the Captain's initiation of the Cabin's Smoke Evacuation Procedure. At 0024 the smoke had cleared substantially. At no time were visible flames detected. At 0029 the aircraft touched down with little visible smoke and the temperature had returned to ambient. The smoke-temperature signatures are shown in Figure 12.

SCENARIO 8 - PROBLEM ANALYSIS.

Background. This fire occurred about half way through a scheduled three-hour flight. It was a smoldering fire in a closet which contained coats as well as hanging luggage. It was not possible to determine the exact source, but it was most likely smoking material left in a coat while still lighted or a spontaneous combustion of some flammable material. The incident took place over an area in which there are several available alternate airfields.

Detection of the Fire. Initial detection was by a passenger who smelled smoke; an Attendant investigated and found smoke issuing from the closet. This initial detection took place when the fire had smoldered for a relatively long time. Smoke and/or heat detectors in the closet would have probably detected the incident sooner.

Localization of the Fire. The site of this incident was quickly and easily determined when the smoke was detected. The location was confirmed when the

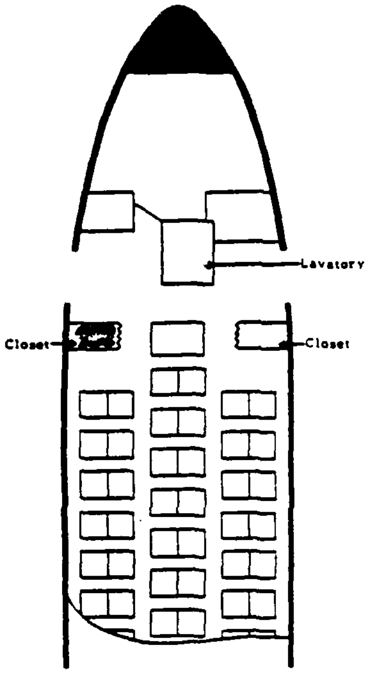

FIGURE 11A. SMOLDERING FIRE IN CLOSET

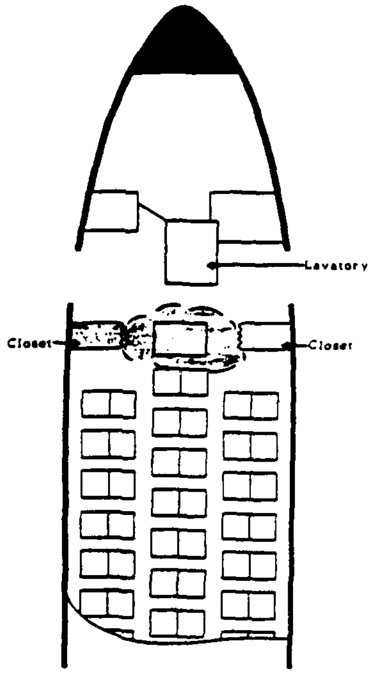

FIGURE 11B. SMOKE LEAKS FROM CLOSET, IS DETECTED IN PASSENGER CABIN

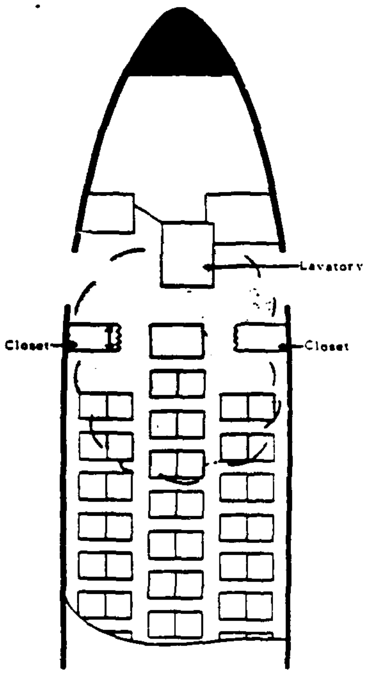

FIGURE 11C. SMOKE IN PASSENGER CABIN INCREASED BY OPENING/CLOSING CLOSET DOOR

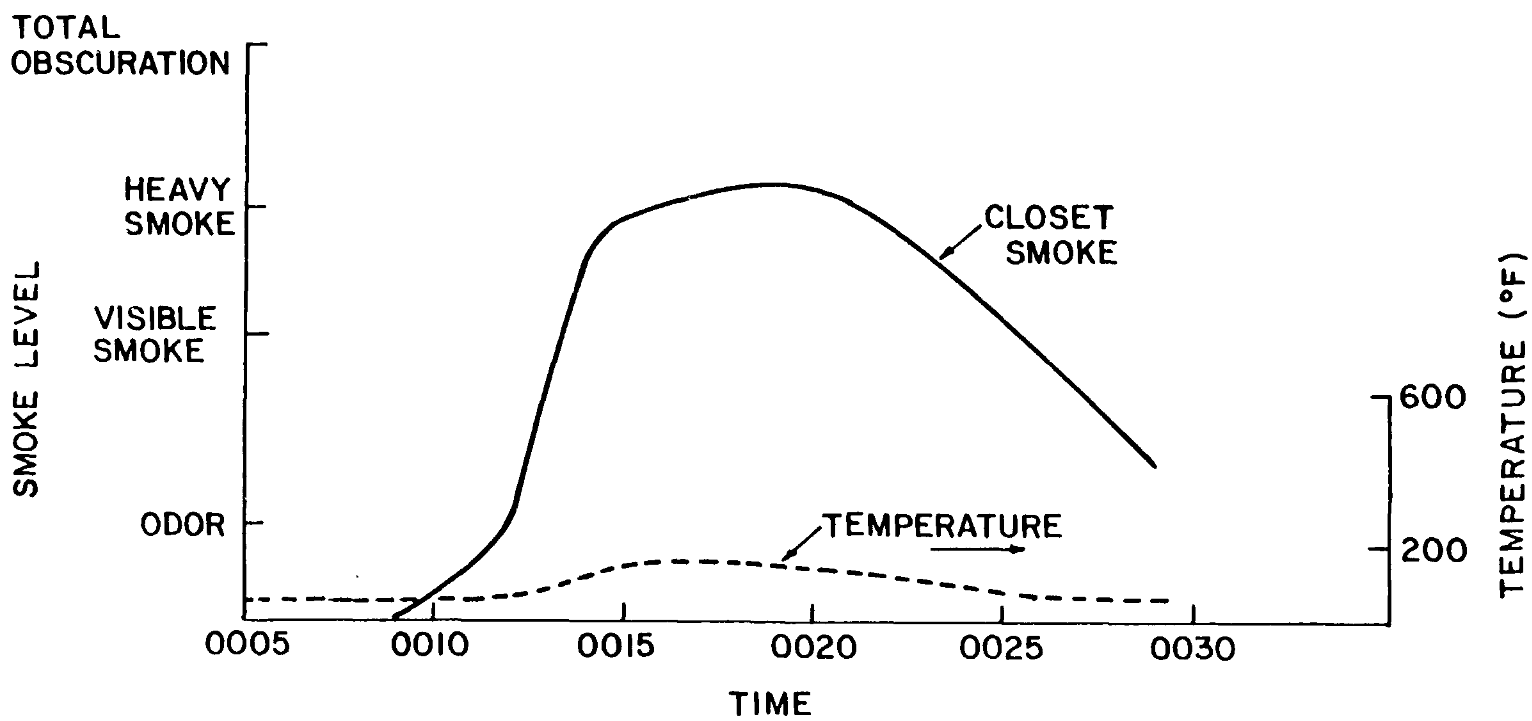

FIGURE 12. SCENARIO 8: SMOKE-TEMPERATURE SIGNATURES

closet contents were removed to apply the extinguishing agent. Until that was done, the possibility existed that the fire was remote from the closet and that the smoke was simply moving through and out of the closet.

Identification of Fire Severity. While the issue of severity was not explicitly addressed in the course of this incident, the description of the smoke/fire given to the Captain led him to order the use of extinguishers. The suggestion is clear that he assessed the severity as being beyond a simpler response (such as beating out a glowing ember).

Evaluation of Situation and Selection of Action. The Captain evaluated the situation as being severe enough to warrant the use of extinguishers and the immediate diversion of the flight to the nearest appropriate airfield. This assessment was made quickly and was appropriate. Subsequent actions: to divert, to ventilate the smoke and finally to conduct an emergency evacuation, were also timely and appropriate.

Conclusions. This incident was handled in an effective and timely way by the crew. Earlier detection might have resulted in less smoke accumulation which might have made the ventilation and the emergency evacuation unnecessary.

SCENARIO 8 - ACES ANALYSIS. This scenario involves a smoldering fire in a clothes closet presumably ignited by lighted smoking material accidentally left in a passenger's coat or luggage. Actual detection was by a passenger who detected the odor of smoke. It is shown in the fire narrative that smoke was generated as early as nine minutes after midnight--0009. The ACES system would have sensed smoke at that time and would have almost immediately determined a positive and growing rate of rise in smoke. This would have generated a s.)ke alert and the ACES would have reset the heat redline. Meanwhile, the overall heat in the closet had not yet increased over ambient. The ACES smoke detector would have determined a continued positive rate of rise. The rate was initially growing slowly but at about 0012 it began to grow rapidly. The ACES system would have issued a smoke alarm at about 0011 or 0012. (This is approximately the same time that the passenger actually noticed the smoke odor.) When the ACES went into smoke alarm it would have also provided the precise location of the incident and forced the display of appropriate emergency procedures.

The ACES benefit in this situation is primarily that the location is identified and that the procedures/checklists are made immediately available. The specific characteristics of this incident are such that the ACES did not provide an earlier detection than did the "human sensor". This should not be unexpected in incidents that occur in or near occupied spaces. It must be remembered, however, that prompt, reliable detection of an incident in any not readily accessible space such as a closet could provide a very valuable amount of time for emergency response.

TABLE 8. SCENARIO 8 - TIMELINE SUMMARY

ACES BENEFIT	System alarm by 0011/0012		Provide crew with the exact location and appropriate emergency procedures				
ACTUAL RESPONSE	FA makes visual inspection	Report to Captain	Deploy extinguishers; decide to declare emergency	Begin descent; decide to evacuate smoke if fire out	Monitor smoke removal	Make full effort stop	
ACTUAL DETECTION	Passenger smell	FA visual	Same	Same	Same	Same	Same
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Odor	Odor closet contents	Same	Same	Same	Same	Same
COMBUSTION EVIDENCE AVAILABLE	Smoke; small heat rise	Increasing smoke and heat rise	Same	Same	Decreasing smoke heat reduced	Little smoke temperature at ambient	Same
EVENT	Passenger report	Visual inspection	Report to Captain	Declares emergency	Initiates smoke removal	Touchdown	Emergency evacuation
TIME	(0012)	(0013)	(0014)	(0017)	(0022)	(0029)	(0034)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Descent	Landing	Parked

SCENARIO 9 - AIR CONDITIONING PACK SMOKE.

SCENARIO 9 - DESCRIPTION. A narrow body twin-jet aircraft was scheduled to operate from Kansas City International to Seattle/Tacoma with a full passenger load. Departure was scheduled for 2200 hours and the pushback was on schedule. After a normal departure, the flight was cleared by ATC to flight level (FL) 310 for the cruise portion.

At 2305 the cabin rapidly began to fill with acrid, oily-smelling smoke later found to be from the left air conditioning pack. The flight crew received notice of the smoke in the passenger cabin at 2306 when the Flight Attendant from first class entered the cockpit with a report of smoke of unknown type and origin and the Attendants in the aft cabin called on the intercom.

The Captain immediately directed the First Officer to determine if an electrical failure was the source of the smoke. He also instructed the Attendant in the aft cabin to remain on the intercom and the Attendant from the forward cabin to return to calm the passengers. He made sure that the cockpit door was securely fastened. The First Officer scanned the overhead panel to check for a tripped circuit breaker. He found none. At 2308 he reported to the Captain that all circuit breakers were in.

The Captain immediately inquired of the Attendant on the intercom whether any fire source was visible. Upon receiving a negative response, he announced to the First Officer that he suspected an air conditioning pack problem. Together they scanned the instruments looking for a problem sign. At 2310 the Captain initiated the Air Conditioning Pack Checklist which included shutting off the right-hand pack. He also notified ATC of the situation asking that lower altitudes be cleared and requested a report of landing conditions at Denver, the nearest airport at which his company had operations.

At 2312 the Attendants reported a dramatic increase in smoke. At the same time, the trip reset switch for the left-hand pack tripped. The Captain correctly interpreted these signs, and at 2313 ordered the right-hand pack back on line and the left totally shut down. He then requested the Smoke Removal Checklist which the First Officer retrieved from the FCOM. After donning their oxygen masks and smoke goggles and going to 100 percent oxygen, the checklist was initiated. It was interrupted by the fire warning indication for the left (No. 1) engine.

At 2315 the Captain ordered the engine shut down and the discharge of both extinguisher bottles for the No. 1 engine. He then notified ATC of an emergency, requested immediate clearance to a lower altitude and a clearance direct to Denver.

At 2316 the flight was cleared for an immediate descent to 10,000 feet and told to standby for vectors to Stapleton International. The Smoke Removal Checklist was resumed and completed at 2318. The Attendants reported that the smoke situation had stabilized, but that some passengers were complaining.

At 2319 clearance direct to Denver was received and the Captain was asked whether he wanted ARFF equipment to meet the flight. Still uncertain about the cause of the smoke and because of the engine fire and shutdown, equipment was requested. Medical support was also requested because of the extensive passenger smoke inhalation.

The rapid, single engine descent in mountainous terrain occupied most of the crew's attention. At 2326 the flight leveled out at 10,000 feet and the outflow valves opened fully. This resulted in a noticeable reduction in smoke density. Touchdown occurred at 2342 and a maximum effort stop was made to minimize the time until the doors could be opened. As soon as the aircraft stopped, the Captain ordered all doors opened, but chose not to order an emergency evacuation. Several passengers were treated for smoke inhalation and released.

Subsequent investigation revealed that a turbine bearing had failed and the smoke was apparently generated by overheating lubricant and later by overheated insulation and plastic components. It was also determined that there had been a fire involving lubricating oil in the No. 1 engine; and that fire was extinguished by the system activated by the Captain at 2315.

SCENARIO 9 - FIRE NARRATIVE. The scenario consists of two separate unrelated smoke and fire conditions which occurred during the flight. For this study's purposes, only the air conditioning pack smoke narrative is described.

In this incident there was no fire. The smoke that appeared in the cabin was generated by the failure of a turbine fan bearing. Initially, the bearing overheated causing the lubricant to smoke. Eventually the bearing seized and insulation and plastic components in and adjacent to the turbine became overheated producing additional smoke. The trip reset switch was tripped by the short circuiting in the pack motor. The smoke signatures of this incident are shown Figure 13.

SCENARIO 9 - PROBLEM ANALYSIS.

Background. This incident was the result of two unrelated events which together created an unusually stressful and potentially hazardous situation. Smoke was distributed throughout the aircraft more or less uniformly leading to the diagnosis of a fault in an air conditioning pack. Since there was no failure indication, the Captain followed specified procedures and as a consequence shut down the right-hand pack. The smoke situation continued to worsen and the left-hand pack reset switch tripped. The right-hand pack was then restored to service by the Captain who also ensured that the failed left-hand pack was totally shut down. At this time the second event occurred: Number One Engine Fire Warning was activated. The appropriate engine fire and shutdown procedures were employed. Smoke persisted in the cabin and with one pack inoperative, the remaining pack could not quickly ventilate the cabin. In addition, the burden of making a single-engine emergency descent, approach and landing greatly increased workload and stress on the Captain and First Officer. This incident occurred over mountainous terrain where only one alternate airfield was reasonably available.

Detection of the Fire. Initial detection of the pack-related event was by the appearance of smoke in the cabin. While it was assumed that a pack was the source, there was no positive detection/location of the incident until the left-hand pack reached a state that tripped its reset switch. (This occurred seven minutes after smoke first appeared.) Meanwhile, specified procedures had resulted in the right-hand pack having been shut down. When the switch tripped, this situation was corrected and the smoke quantity began to stabilize and eventually diminish.

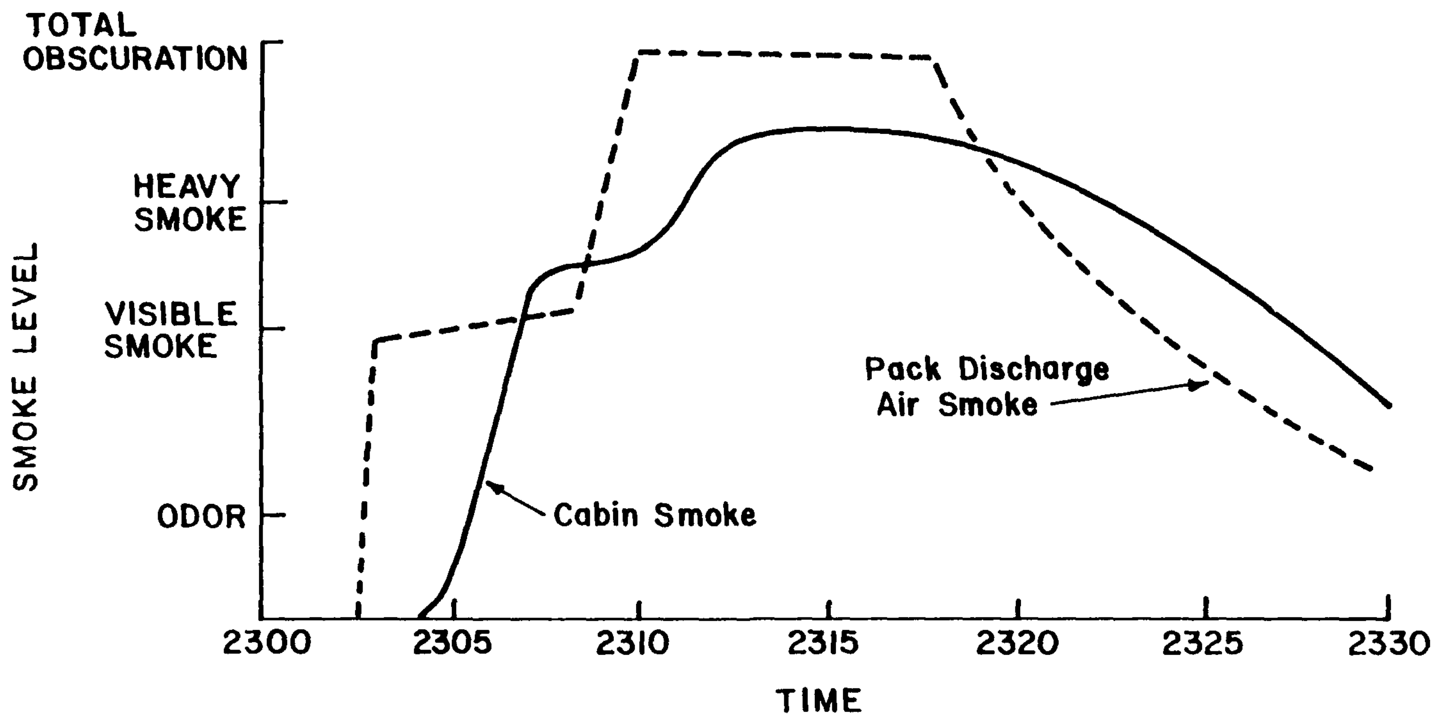

FIGURE 13. SCENARIO 9: SMOKE SIGNATURES

Detection of the second event (engine fire) was by means of the fire warning indicator which triggered the appropriate emergency response by the crew.

Localization of the Fire. The initial response was to shut down the right-hand pack, in conformance with specified procedures. Since the problem was actually in the left-hand pack, that response did not affect the smoke. As evident here, there are abnormal situations that produce smoke before a pack failure is indicated. The specified procedure in this situation is to shut down the right-hand pack first, essentially as a trial or diagnostic step. It was only when the reset switch tripped that positive localization was possible. The engine fire, of course, was detected and located by the Firing Warning alarm.

Identification of Fire Severity. In this incident severity as such was not a critical issue: once the malfunctioning pack was identified and shut down, the movement of smoke into the cabin was stopped. Ventilation by means of the remaining pack was accomplished at the full capacity of that pack without regard to the severity of the event.

Evaluation of Situation and Selection of of Action. In this incident the immediate evaluation--pack problem--was correct and timely. The response of shutting down the pack which was not the source was made by procedure. There was no possible means of identifying the source until the reset tripped. All other actions including diversion, maximum effort stop and opening doors immediately were warranted and were completed successfully.

Conclusions. Even though, in this incident, the cabin filled with smoke which proved difficult to ventilate, all of the responses were correct and properly executed. Without other cues, the shutdown of the wrong air conditioning pack could not have been avoided. Then with only one operative pack there was only limited capacity for ventilating the smoke from the cabin. The response to the engine fire warning was timely and correct.

SCENARIO 9 - ACES ANALYSIS. This scenario involved two separate events: smoke from an air conditioning pack overheat and fire in the No. 1 engine. The former event is of direct concern to an ACES system. The latter is outside the ACES system definition but diverted the crew's attention from the first event, thereby affecting their response.

The ACES system would have sensed smoke at about 2303 and determined almost immediately a positive, growing rate of rise in smoke. This would have been two minutes before the actual visual detection took place. The ACES system would have initiated a smoke alarm, reset the heat redline and forced the display of appropriate emergency procedures and checklists.

In this incident, earlier detection by ACES (being only two minutes) is probably of itself a marginal benefit. By locating the smoke source precisely, the ACES system would have provided substantial benefit. In the actual occurrence. the crew shut down the pack that was not overheating thereby allowing the smoke to increase significantly and continue being distributed throughout the cabin. The true benefit of the ACES system, then, is best expressed in terms of time to respond correctly. In the actual event, smoke appeared at 2305 and not until 2313 was the malfunctioning unit shut down. Thus, for eight minutes after detection smoke continued to be generated and distributed throughout the passenger compartment. Under the ACES system,

the source would have been identified immediately and, allowing one minute for response, the offending unit could have been shut down at about 2304. This represents about nine minutes less exposure of the crew and passengers and the aircraft to the noxious smoke. The fire narrative indicates that those nine minutes included the time of most intense smoke increase which only compounds the potential benefit.

TABLE 9. SCENARIO 9 - TIMELINE SUMMARY

ACES BENEFIT	System alarms at 2303		Precise location of the smoke source		Earlier shutdown of the left pack at 2304		Immediate display of appropriate emergency procedures and checklists		
ACTUAL RESPONSE	Notify cockpit	Notify cockpit	Panel scanning	Shut down right pack per check-list	Right pack back on; left pack off; Smoke Removal Checklist	Left engine fire pro-cedure; declare emer-gency; divert to Denver	Same	Same	
ACTUAL DETECTION	Atten-dants and passengers	Same	Same	Same	Cockpit crew	Same	Same	Same	
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Pack operation	Same	No breakers tripped	No heat in-crease in pressurized areas	Left pack trip reset	Same	Same	Outflow open	
COMBUSTION EVIDENCE AVAILABLE	Smoke	Smoke	Same	Same	Increasing smoke	Smoke stable or decreasing	Decreasing smoke	Rapid smoke decrease	
EVENT	Smoke noticed in cabin	Cockpit notified	Check for circuit breaker trip	Right pack shutdown	Smoke reported increasing	Left engine shut down	Complete Smoke Removal Checklist	Outflow valve open	Touchdown
TIME	(2305)	(2306)	(2308)	(2310)	(2312)	(2314)	(2318)	(2326)	(2342)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Descent	Cruise	

SCENARIO 10 - CONCEALED FIRE (CHEEK).

SCENARIO 10 - DESCRIPTION. A wide body tri-jet aircraft was operating nonstop from Atlanta's Hartsfield International to Seattle/Tacoma International with 198 passengers and a crew of 14 (3 flight and 11 cabin). The flight departed on schedule at 1000. After following a standard instrument departure, the flight was cleared to flight level 310 for the transcontinental trip.

Passenger service included a full hot meal. This was to be heated in the ovens in the lower deck galley and distributed in serving carts. Preparation for the meal service began at 1130, and all food preparation ended by 1153.

At some time after 1130, but unknown to the crew or passengers, lint and debris in the fuselage cheek adjacent to a galley oven began to smolder. It was later determined that insulation on a power cable had been accidentally nicked and there had been intermittent arcing. This arcing ignited the debris in the cheek, but did not trip a circuit breaker. The smoldering then became an active fire; as a result of this burning, a hydraulic line developed a small leak. Hydraulic fluid escaped and began to burn and generate a large volume of smoke. This smoke migrated through the cheek area and, at 1155 the fire penetrated the galley wall allowing smoke to pour into the galley. The galley smoke detector tripped at 1156 when the aircraft was 160 miles north of Omaha, Nebraska (approximately over Sioux City, Iowa).

Upon receiving the galley smoke warning in the cockpit, the Captain confirmed that no one was in the galley and the crew began to execute the standard emergency procedures. The First Officer retrieved the checklist from the FCOM at 1157 and called for shutting down the galley power switches. This was immediately done by the Flight Engineer. They then proceeded through the remainder of the checklist.

At 1159 the Captain instructed the Flight Engineer to don his smoke mask and oxygen bottle and take a fire extinguisher down the lift to the galley. The Captain then notified his company's operations center of the problem and reported the situation to the en route center. At 1200, in response to a low pressure alarm, the affected hydraulic system was shut down.

The Flight Engineer complied with the Captain's directive and entered the galley at 1204. He checked that the galley ceiling air vents were open and then turned his attention to the oven area from which the smoke was emanating. Seeing smoke from the oven areas, he discharged the fire extinguisher at the ovens. He then exited the galley and returned to the cockpit at 1210. The Flight Engineer reported to the Captain that he thought the fire was under control. At the same time, the Senior Flight Attendant called the cockpit and said he could see smoke in the galley-lift shaft. The Captain then instructed the Flight Engineer to return to the galley for an additional check.

At 1228 the Flight Engineer attempted to descend the lift wearing his smoke mask and oxygen bottle. The smoke was so thick that he could not see when he reached the galley. He groped for the intercom and informed the Captain that the smoke was obviously still being generated. He recommended an immediate landing at the nearest suitable airport and maximum electrical load shedding on the assumption that the fire was electrical in origin. At this time, the flight was 40 miles due east of Pierre, South Dakota and still at flight level 310.

The Captain instructed the First Officer to execute the Smoke Evacuation Checklist and begin shedding electrical load while waiting for the Flight Engineer to return. He then contacted the en route center and notified them of the emergency and his desire to make an immediate descent to land. He received immediate clearance to 16,000 feet and began a descent. At 1232 the Captain reached for his charts to select an appropriate landing site. As he was reading the charts, the Flight Engineer returned to the cockpit. The Captain then instructed him to take over the checklist tasks while the First Officer notified the Cabin Attendants and passengers. The Senior Cabin Attendant reported only minimal smoke in the passenger areas, but it was not certain that the fire was out.

The Captain rejected a landing at Pierre, the nearest field, because of inadequate runway length. Rapid City was also rejected as inadequate to handle a severe emergency to a plane of this size. Minneapolis/St. Paul at 400 miles and Omaha at 340 miles seemed to be the best choices for commercial fields, and Ellsworth Air Force Base at 174 miles was the closest suitable field. ATC informed the Captain that the weather at Omaha was marginal with solid overcast at 1,200 ft in rain squalls and fog. Minneapolis and Ellsworth showed acceptable weather.

With most power shut down and uncertainty as to whether the smoke source had been eliminated, the Captain elected to land at Ellsworth. He requested clearance for a direct routing and a precision radar approach. ATC told him to standby at 1235. The Captain told the First Officer to contact company operations and inform them that he was going to Ellsworth. He also requested the Flight Engineer to maintain constant intercom communication with the Senior Cabin Attendant to provide cabin smoke reports.

At 1236 ATC gave vectors for Ellsworth and cleared the flight for an immediate descent at Captain's discretion to 2,000 feet. At 1238 ATC informed the Captain that Ellsworth had been notified, gave the Captain the Ellsworth tower frequency and asked if the Captain was requesting equipment. The Captain declined equipment saying that he thought the smoke source had been eliminated.

At 1242 the Captain contacted Ellsworth tower and again declined equipment. The tower confirmed a radar contact and gave him vectors.

At 1251 the Flight Engineer told the Captain that the smoke had definitely entered the cabin, and the passengers were starting to complain. The Captain asked if there were any visible signs of fire in the cabin and was told no. He asked for regular updates. At 1253 he told the First Officer to notify Ellsworth that ARFF equipment would be required and that he was planning for a maximum effort stop and emergency evacuation. He then asked the Flight Engineer to tell the Senior Cabin Attendant to come forward for a briefing.

By 1259 the crew and passengers had been briefed and were preparing for the emergency landing and evacuation. The smoke level was increasing in the center of the aircraft so the Attendants moved as many passengers as possible to seats forward and aft. The Captain ordered the Flight Crew to don oxygen masks and go on 100 percent oxygen even though there was no smoke in the cockpit.

Touchdown occurred at 1310 and the Captain brought the plane to a stop in 5,300 feet with the ARFF crews following. Escape chutes were deployed and everyone exited within two minutes. There were 30 minor injuries during the evacuation, and 10 people complained of discomfort from the smoke. Firefighters removed panelling and completely extinguished the fire.

SCENARIO 10 - FIRE NARRATIVE. At approximately 1145, lint and loose debris in the cheek area, next to the galley oven, were ignited by an intermittent electrical arc. The arc was the result of mechanical damage sustained by power cables. As the fire developed, the smoke it produced rose vertically and was distributed overhead, fore and aft within the cheek area. Five minutes later, a small leak developed in an aluminum hydraulic line as a result of contact with the flame. Fluid leaking from the hydraulic line ignited and, at approximately 1155, burned through into the galley area. At 1200, power was shutdown to the involved hydraulic system and the fuel flow from the leak quickly diminished to zero. By 1204 the galley was completely filled with smoke, restricting visibility. By 1210 the fire had diminished because the available fuel was being depleted, however, the cheek area remained filled with smoke. Smoke continued to flow through the hole in the wall into the galley area. At 1225 smoke was visible in the passenger cabin. By 1228 the galley was totally obscured. The fire in the cheek area continued to diminish as the limited fuel was consumed and burned out, at approximately 1240. Smoke continued to move through the galley and up the elevator shaft into the passenger compartment area. At 1251 the smoke became thicker in the passenger cabin. Smoke did not enter into the cockpit and the aircraft touched down at 1310. The smoke-temperature signatures are shown in Figure 14.

SCENARIO 10 - PROBLEM ANALYSIS.

Background. This incident involved a fire ignited by overheated electrical wires in the space between the interior galley (lower lobe) wall and the fuselage in the cheek of a wide body tri-jet. Smoke was detected at about 2 hours into the flight issuing from the galley. The source was presumed to be in the galley, and an extinguisher was discharged toward the oven closest to the smoke flow. An emergency landing was made at a military airfield and the passengers exited by the emergency slides following a maximum effort stop.

Detection of the Fire. In this incident, the smoke was initially detected by a sensor located in the affected galley with an alarm in the cockpit. Later, smoke was seen in the galley and the lift as well as in the cabin. No active fire was ever detected in flight.

Localization of the Fire. Because the galley alarm activated and because the smoke was visible in the galley and lift, it was assumed that the source was in the galley. On the second trip to the galley, the Flight Engineer was unable to see through the smoke in the galley and could not confirm the exact location.

Identification of Fire Severity. The Flight Engineer on his first trip to the area discharged an extinguisher into the galley adjacent to and at the ovens. He then reported that the fire was, "under control". On his second trip to the oven, he was unable to see through the smoke in the galley and correctly decided that there was a persistent, strong source of smoke. He advised the Captain to make an emergency landing as soon as possible.

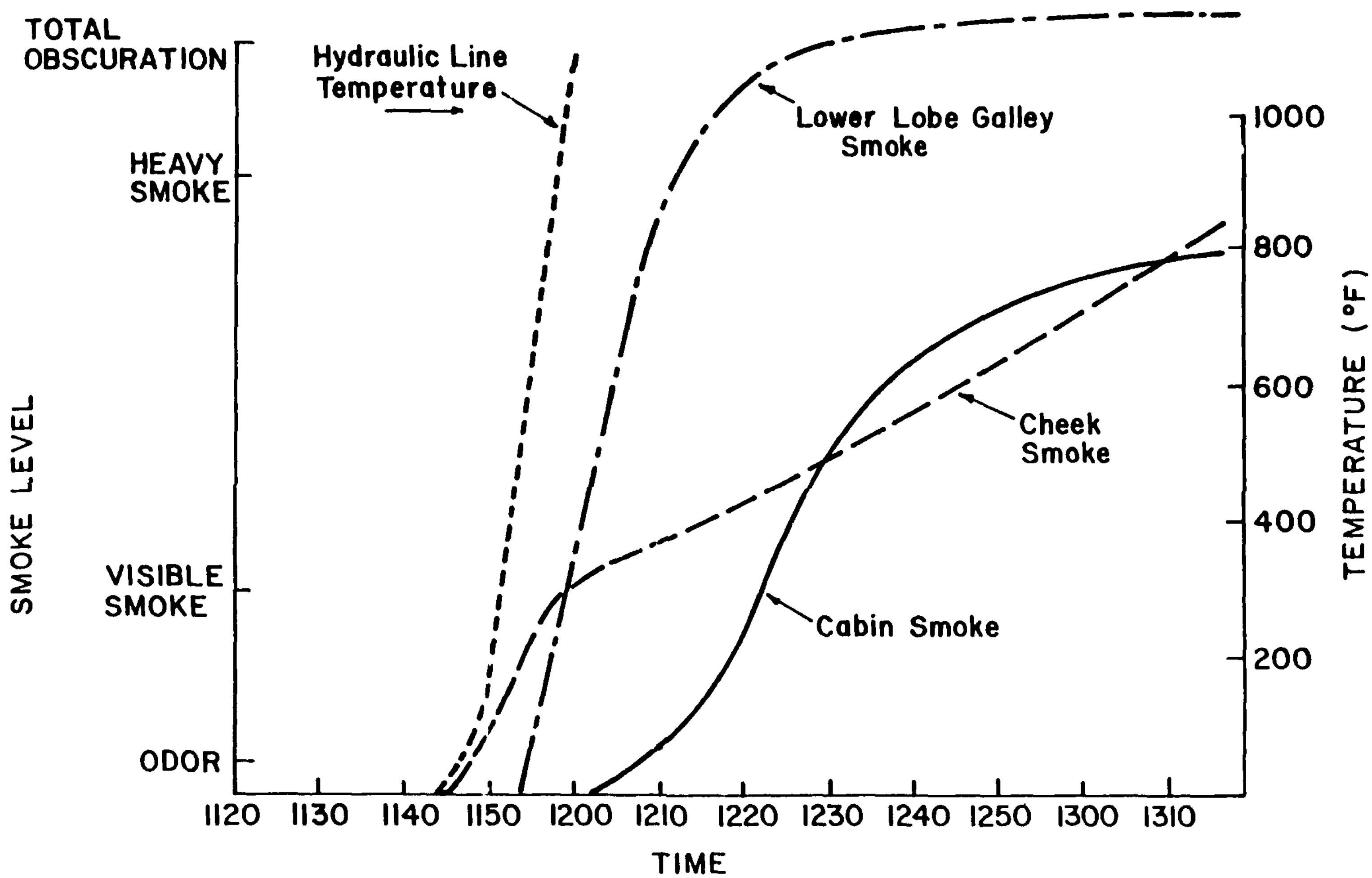

FIGURE 14. SCENARIO 10: SMOKE-TEMPERATURE SIGNATURES

Evaluation of Situation and Selection of Action. The Flight Engineer, when confronted with impenetrable smoke correctly assessed the situation and advised the only feasible action which the Captain implemented: immediate diversion and emergency landing. Subsequently, the Captain elected to use the closest adequate airfield even though it is a military field and then to make a maximum effort stop and evacuate the passengers by slides. All of these were appropriate and were successfully implemented.

Conclusion. Overall, this incident was properly handled within the existing system structure. Rapid, positive detection of the source could have allowed the crew to penetrate the galley wall and apply an extinguisher more directly (provided that tools were available and the procedure was allowed). More remotely possible would have been the identification of the involved wiring so that breakers could have been pulled.

SCENARIO 10 - ACES ANALYSIS. In this scenario, fire in a cheek area adjacent to a lower lobe galley ignited and developed unknown to passengers or crew. The fire led to a leak in a hydraulic line which added fuel; this increased fire penetrated the galley wall and filled the galley area with smoke, triggering an alarm at 1156.

The smoke in the lower lobe galley increased almost instantaneously to total obscuration. The ACES with a sensor unit in the galley system would have sensed smoke at about the same time as the current system did. In addition, the ACES system would have almost immediately determined a rapidly growing, positive rate of rise. This would have first set a smoke alert and then a smoke alarm because of the persistent rate of rise. Meanwhile, after about 3 to 5 minutes, the ACES heat detector would have sensed heat above ambient with a rapid rise rate and a positive fire alarm would have been established at about 1200 or 1201*. Thus, the ACES system (using only the galley mounted sensors) would have informed the crew of a positive fire and forced display of appropriate emergency procedures by no later than 1201. Assuming a reasonable time for reaction and for requesting and receiving an emergency clearance, this flight could have been en route to an emergency diversion field by no later than 1205. This did not occur in the scenario until 1204. Thus, the ACES benefit in this situation would have been a much earlier decision to declare an emergency with the possibility of diverting to a closer suitable field. Further, the information that the incident was a true fire might have influenced the way in which the extinguisher attack was mounted. A landing could have been made as early as 1205 with this ACES configuration.

The above discussion is based only on sensing in the galley. A more complete and more sophisticated ACES could have included cheek sensors in the affected area. Both heat and smoke sensing in that area combined with monitoring of the electrical system would have sensed the arcing that ignited the fire as well as the resulting combustion. The fire narrative shows that this could have occurred as early as 1145 and certainly by 1150. The positive alarm of fire at that time would have dramatically increased the time available for diversion and other appropriate

*The heat signature in the galley would parallel the "hydraulic line" heat curve shown in Figure 14. The rate of rise in the galley would be positive but somewhat more shallow.

emergency procedures. Since the fire was in a cheek area, this very early detection could not have been exploited in an attack on the fire under current procedures. If fire ports or the use of forcible access should be adopted, early detection would permit a direct and more successful attack. This ACES configuration would have permitted landing at a diversion field as early as 1150.

TABLE 10. SCENARIO 10 - TIMELINE SUMMARY

ACES BENEFIT	System alarm as early as 1145-1150					Immediate display of procedures/checklists; precise location of fire		Earlier direct diversion (at 1150-1205)	
ACTUAL RESPONSE				Begin locali-zation	Go to scene and conduct checklist	Leave galley area	2nd galley inspection	Decision to land	Review alter-natives; select Ellsworth
ACTUAL DETECTION				Smoke sensor	Sensor and visual	Same	Attendants	2nd Flight Engineer confirmation	Same
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Abnormal current		Smoke; heat	No current draw by ovens	Smoke level not decreased by power removal	Same	Smoke not abating	Same	Same
COMBUSTION AVAILABLE EVIDENCE	Local tempera-ture rise			Smoke; heat	Same	Same	Smoke in cabin as well as smoke/heat in galley	Galley obscured by smoke	Same
EVENT	Electri-cal arc	Hydraulic line failure	Fire penetrates wall	Galley smoke detector trips	Flight En-gineer sent to galley	Extinguisher discharged at oven	Cockpit notified of smoke in cabin	Flight Engin-eer returned to galley	Decision to go to Ellsworth
TIME	(1145)	(1150)	(1155)	(1156)	(1159)	(1209)	(1225)	(1228)	(1234)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise	Cruise

TABLE 10. SCENARIO 10 - TIMELINE SUMMARY (Continued)

ACES BENEFIT	Touchdown as early 1200 (if Omaha weather permits)	
ACTUAL RESPONSE	Passenger complaints	
ACTUAL DETECTION	Same	
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Same	
COMBUSTION EVIDENCE AVAILABLE	Thickened smoke in cabin	
EVENT	Request for emergency equipment	Touchdown
TIME	(1253)	(1310)
FLIGHT PHASE	Descent	

SCENARIO 11 - GALLEY FIRE.

SCENARIO 11 - DESCRIPTION. A narrow body twin-jet was operating nonstop from Miami International to Newark International with a 2205 departure time. A total of 80 passengers and a crew of 7 (Captain, First Officer and 5 Cabin Attendants) were on board. The flight left the gate on time and took off at 2219.

After reaching the assigned altitude, at 2239, a snack was served. At 2301 the litter had been cleared and the main cabin lights were extinguished to allow the passengers to sleep. Two wrapped snack dishes were inadvertently left in one of the warming ovens in the aft galley. After about 10 additional minutes of heating, they began to smolder. By 2315 smoke was being emitted from the oven into the galley. At this point, the aircraft was approximately 45 miles east of Charleston, South Carolina at flight level 310.

The smoke initially went unnoticed by both the crew and the passengers. At 2322 a passenger walking down the aisle to the lavatories saw smoke coming from the galley and alerted a Flight Attendant. She in turn told another Attendant to notify the cockpit while she went to retrieve a hand fire extinguisher. At 2324 the First Officer was notified of smoke in the galley. He told the Captain who ordered the aft galley breakers to be pulled. The First Officer then scanned the panel and pulled the breakers at 2326.

The smoke was so thick in the galley that the Flight Attendant with the hand extinguisher could not see to discharge the extinguisher at the base of the fire. At 2328 she called the cockpit and notified the First Officer that smoke was apparently still being generated. The Captain then notified ATC of a possible emergency and requested immediate clearance to a lower altitude. He was cleared to flight level 180 and began a descent. At the same time, he instructed the First Officer to don his smoke mask and portable oxygen bottle, and take another extinguisher and go back to take control of the situation. The First Officer exited the cockpit at 2341 and arrived at the galley at 2342. With the aid of his smoke equipment he could see that the smoke was coming from the oven. He opened the door and discharged his fire extinguisher at the food trays inside. He then used one of the serving utensils to extract the food trays and examine them. Convinced that they were the only source of the smoke, he exited the galley and went to the intercom to report to the Captain.

The Captain meanwhile retrieved the FCOM and found the procedures for smoke removal. He set the landing altitude selector to 9,500 ft and placed the auto pressure control of the air conditioning system on maximum. He also turned off the left and right recirculation fan switches and illuminated the "No Smoking" and "Fasten Seatbelts" signs. Finding the FCOM checklist and executing the steps took until 2345. The Captain then made a preliminary announcement to calm the passengers and turned to the task of finding a suitable landing site.

The navigation display of the Flight Management System showed Wilmington, N.C. as the closest airport. Since his company had operations into Wilmington, the Captain called ATC and requested clearance direct to Wilmington. He declared an emergency and requested ARFF equipment. At 2349 ATC granted clearance to Wilmington and to descend to 2,000 feet. The Captain began programming the Flight Management System for the approach. At 2351 the Captain informed him to notify the Attendants to move all passengers as far

forward as possible, directed him to return to the cockpit and prepare for an immediate approach to Wilmington.

The Captain then called ATC and explained that the fire was out, but there was still considerable smoke in the cabin. He cancelled the request for equipment, but asked for EMTs to treat any possible problems of smoke inhalation.

At 0005 the plane touched down at Wilmington. After roll out, the captain ordered the forward and aft left passenger doors opened for ventilation and taxied to the terminal. Several passengers complained of burning eyes and were examined by the EMTs and released. The plane was thoroughly inspected and allowed to ventilate and then returned to service.

SCENARIO 11 - FIRE NARRATIVE. In this incident food left inadvertently in the aft galley warming oven continued to be heated and consequently generated smoke at approximately 2310. The smoke was initially contained within the oven. However, at 2315 the smoke emitted from the oven into the galley. The smoke continued to build up in the aft galley area but was not noticed until 2322. Even after the aft galley circuit breakers had been pulled, the food continued to smolder for more than ten minutes. The food trays never reached the flaming stage and the smoldering material was contained within the oven. The smoldering food was extinguished by use of a fire extinguisher. The smoke signature in the galley is shown in Figure 15.

SCENARIO 11 - PROBLEM ANALYSIS.

Background. This incident involved food dishes being left in a warming oven and the oven left on. Both of these events were by mistake. The food began to smolder and generate smoke. This smoldering fire was extinguished and emergency ventilation was implemented. The flight diverted to the closest alternate field and a normal landing was made.

Detection of the Fire. Initial detection was by a passenger who saw smoke issuing from the galley. There was no detector in this area so the detection and subsequent evaluations were visual. Heat and/or smoke smoke detectors might have sensed the incident earlier resulting perhaps in less smoke in the cabin.

Localization of the Fire. The site of this incident was established when detection was made in the galley area. The exact site (in the galley oven) was determined when the First Officer used an extinguisher.

Identification of Fire Severity. The First Officer correctly assessed the severity when he examined the galley and applied the extinguisher to the oven and its contents. He advised the further response of diverting to the nearest adequate airfield, which the Captain implemented.

Evaluation of Situation and Selection of Action. The First officer went to the galley area with protective equipment ready to attack the fire. When the First Officer arrived at the galley he confirmed the evaluation that it was a controllable fire and extinguished it.

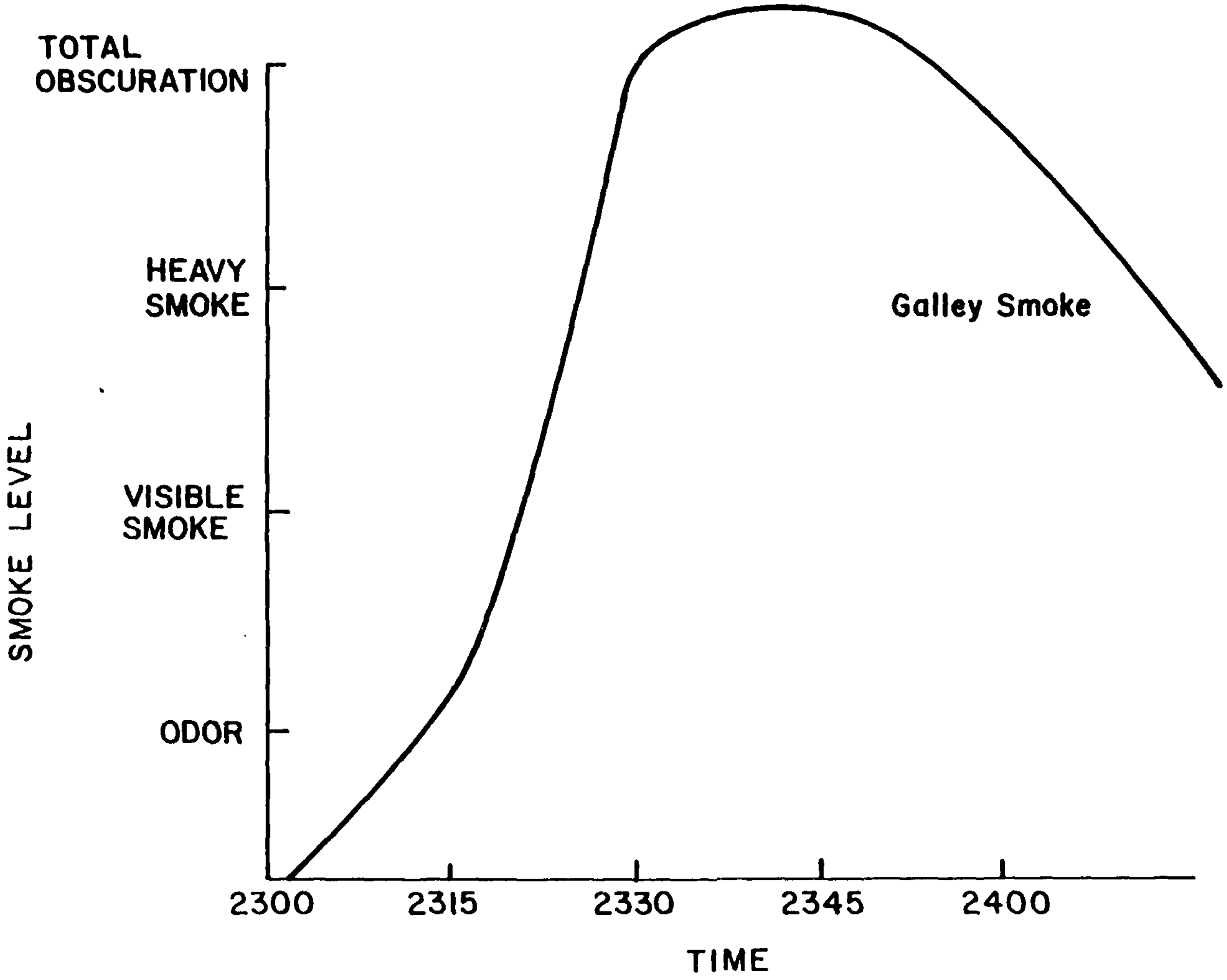

FIGURE 15. SCENARIO 11: GALLEY SMOKE SIGNATURE

Conclusions. This incident was properly handled: the smoke/fire situation was correctly assessed and successful extinguishment was carried out. Because the initial detection was of smoke issuing from the galley, the possibility existed that the source was remote from the galley and that the flow of smoke only passed through the galley. Had that been the case, evaluation and response would have been performed differently.

SCENARIO 11 - ACES ANALYSIS. In this scenario heavy smoke is generated by food trays overheating in a galley oven inadvertently left turned on after food service had been completed. The smoke signature developed for this incident indicates that the ACES system would have sensed smoke as early as about 2305, the ACES would have almost immediately determined a growing, positive rate of rise and established an alert condition. By no later than 2310 the ACES would have established a smoke alarm because of the persistent rate of rise. The ACES system would have reset the redline on the related heat sensor; but no significant heat rise above ambient occurred except very closely adjacent to the oven. Assuming that the ACES was configured with the sensor pair co-located to sense the whole galley area, the smoke alert and warning would have been as described just above. If, as might be done, the oven had been equipped with ACES heat sensing the system would have been able to provide more precise location of the incident and perhaps have detected the fact that the oven had been on longer than was appropriate. That heat sensor data would have been useful, but even if only the overall galley sensing had been in place, the ACES would have warned the crew about 12 to 17 minutes before the smoke was actually seen. Allowing about 2 to 3 minutes for the oven to be shut down, the generation of smoke could have been stopped at no later than 2312, when the smoke was just becoming visible. Smoke removal and any subsequent emergency actions could have proceeded more easily in the lesser amount of smoke.

TABLE 11. SCENARIO 11 - TIMELINE SUMMARY

ACES BENEFIT	System alarms at approximately 2310		Crew would have been been warned 12-17 minutes earlier		Extinguisher used earlier		Earlier smoke removal	
ACTUAL RESPONSE			Notify crew		FO to investigate; descent requested/initiated; Smoke Removal Checklist	FO uses extinguisher		
ACTUAL DETECTION			Passenger sees/smells	Same	Same	FO visual	Same	
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Oven on too long	Same	Odor	Same	Smoke not decreasing after breaker pull	FO sees problem	Same	
COMBUSTION EVIDENCE AVAILABLE		Smoke	Same	Same	Same	Same	Same	
EVENT	Meals left in oven	Smoke in galley	Smoke detected	Breakers pulled	2nd notice to cockpit	Alternate selected/ cleared	Cancel emergency landing	Touchdown
TIME	(2250)	(2315)	(2322)	(2326)	(2328)	(2349)	(2351)	(0005)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Cruise	Descent	Descent	

SCENARIO 12 - HAZARDOUS CARGO FIRE.

SCENARIO 12 - DESCRIPTION. A narrow body four-engine jet aircraft in a cargo-only configuration was on a scheduled cargo flight from John F. Kennedy International Airport (JFK), New York, to Frankfurt, Germany with a scheduled stop at Prestwick, Scotland. The flight departed JFK at 0825 Eastern time. Among its cargo, was a box containing a bottle of nitric acid packed in a wooden crate with sawdust as cushioning material. This crate was loaded in the forward portion of the main cargo compartment. The nature of the contents of the box was not declared at check-in, and the acid was not packaged in accordance with FAA rules.

At about 0830, unknown to the three-man flight crew, the nitric acid spilled into the sawdust and began the process of hypergolic (self-sustaining) combustion. At 0904 with the aircraft approximately 100 miles east of Montreal, smoke from the fire had spread to the cockpit by way of the return air grille and was detected by the crew.

Upon detection of the smoke, the crew concluded, erroneously, that they were dealing with a minor, below-deck electrical fire. They continued to believe this conclusion even though no circuit breakers had popped. They contacted their company's New York operations department (OPS) at JFK and asked whether they should return or divert to Logan International at Boston. Because they had underestimated their problem, they did not plan to divert to the nearest suitable field but, to use an airport at which their company had maintenance and repair facilities.

At 0906 the flight was told by OPS to return to JFK. At the same time, they were handed off by the Boston Center to the Montreal Center. In the confusion, the crew did not hear the frequency specified by the Boston Center for the hand off and took until 0909 to establish contact with Montreal Center. They were given clearance to return to JFK direct at 0910. The smoke in the cockpit was increasing. The smoke detectors in the avionics bay activated.

Also at 0910 the crew decided to go on oxygen. Shortly thereafter at 0911, the Captain realized that reaching JFK safely would be a problem. He therefore radioed OPS and informed them that he was diverting to Logan. He then called Boston Center and requested both direct Boston and an immediate descent to increase his fuel burn. A heading for Boston was given and clearance to descend from flight level 310 to level 180 was granted at 0912.

The Captain requested AFRR coverage at Logan through his OPS department, but he never declared an emergency. At 0914 the Captain asked the First Officer if he had Boston approach plates but received no response. Also at 0914 the Flight Engineer confirmed that the fire warning circuit and alarm were functioning. The Captain gave the airplane to the First Officer and began searching for his own Boston approach plates.

For the next 10 minutes, the crew attempted to prepare for a normal landing at Logan in spite of the thick smoke. They received the field altimeter setting and requested a landing on runway 33. They called their company's operations center at Logan at 0924 to advise of an "electrical fire in the forward end of the airplane." At 0927 they had descended to 2,000 feet and slowed sufficiently to put the gear down and open the cockpit window to try to remove some of the smoke. The open window actually served to draw more smoke into the cockpit.

By 0932 they were 35 miles northeast of Logan at 2,000 feet and notified the tower that they were not declaring an emergency. At 0935 the Captain refused a vector to a 5 mile final, requested a "quick in" and was cleared to the Boston VOR. Immediately thereafter, the fire burned through electrical cables and cut off radio transmission. The aircraft crashed short of the runway at 0940 after a series of yawing and rolling maneuvers. These were attributed to the fact that the yaw damper has been rendered inoperative in the normal load shedding prescribed in the Flight Crew Operations Manual which the Flight Engineer had implemented at 0935.. The Captain was unaware that the Flight Engineer had executed the smoke countermeasure procedures. *All aboard perished.*

SCENARIO 12 - FIRE NARRATIVE. While climbing out after takeoff, the aircraft passed through an area of moderate-to-severe turbulence. At that time, an improperly packed container of fuming nitric acid spilled into a bed of sawdust, used as packing material, inside a wooden crate (Figure 16A). Due to the strong oxidizing capability of the nitric acid, combined with the small particle sizes of the sawdust, rapid oxidation took place, quickly resulting in flaming combustion. Temperatures inside the crate rose rapidly and quickly exceeded 1,000°F as the fire broke out of the crate and began to grow rapidly. Since the main deck was nearly filled with cargo, the small volume of the the hazardous cargo area, adjacent to the flight deck bulkhead, rapidly filled with smoke. It began to migrate forward to the cheek area adjacent to the cockpit and below the main cargo deck, to the vicinity of the below-deck avionics bay identified as Lower 41 (Figure 16B). At approximately 0840, the fire was spreading slowly through other cargo on the main deck. Immediately after the fire ignited, temperatures in the hazardous cargo area rose rapidly and reached, perhaps, 800°F at the ceiling and tapered off as the box began to be consumed. As the fire developed slowly through the tightly packed cargo, the temperature in the main cargo area rose and, at 0850, reached about 600°F. By 0904, smoke began to leak into the cockpit via the return air grille (Figure 16C). As the smoke level increased in the cockpit, levels in Lower 41 also rose and at 0910 the smoke detector in that bay activated. By 0914 the main cargo deck was completely obscured in the hazardous cargo area.

Smoke continued to get thicker on the flight deck and vision was sufficiently obscured that small instruments could not be read on the panel (Figure 16D). At 0935 either hot gases or flames from the fire on the main cargo deck caused electrical failures resulting in loss of communication. The aircraft crashed at 0940. The smoke-temperature signatures are shown in Figure 17.

SCENARIO 12 - PROBLEM ANALYSIS.

Background. This incident had its origin in a container of hazardous material--nitric acid which is a hypergol: it initiates combustion on contact with combustible material and supports combustion as it continues to oxidize. This material had not been properly packaged for shipment and it had not been identified in the manifest. At about one-half hour into a trans-atlantic cargo flight the acid spilled igniting adjacent material. The fire was never correctly identified, in part because the crew did not know the acid was on board. Following the appearance of smoke in the cockpit, there was a series of inappropriate decisions and responses. The outcome was a crash--while on a final approach--and fire which killed all three crew members and destroyed the aircraft.

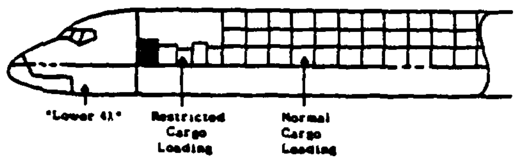

FIGURE 16A. FUMING NITRIC ACID IN WOODEN CRATE

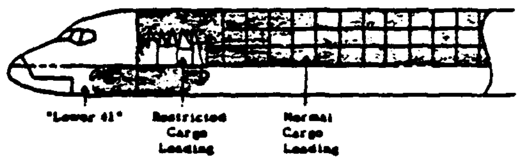

FIGURE 16B. FIRE GREW RAPIDLY--SMOKE FILLED MAIN CARGO DECK AND ENTERED LOWER 41

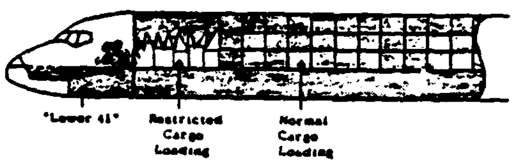

FIGURE 16C. SMOKE LEAKED INTO COCKPIT FROM LOWER 41 VIA RETURN AIR GRILLE

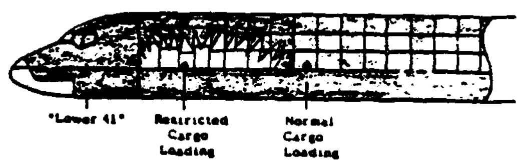

FIGURE 16D. SMOKE OBSCURED SMALL INSTRUMENTS IN COCKPIT

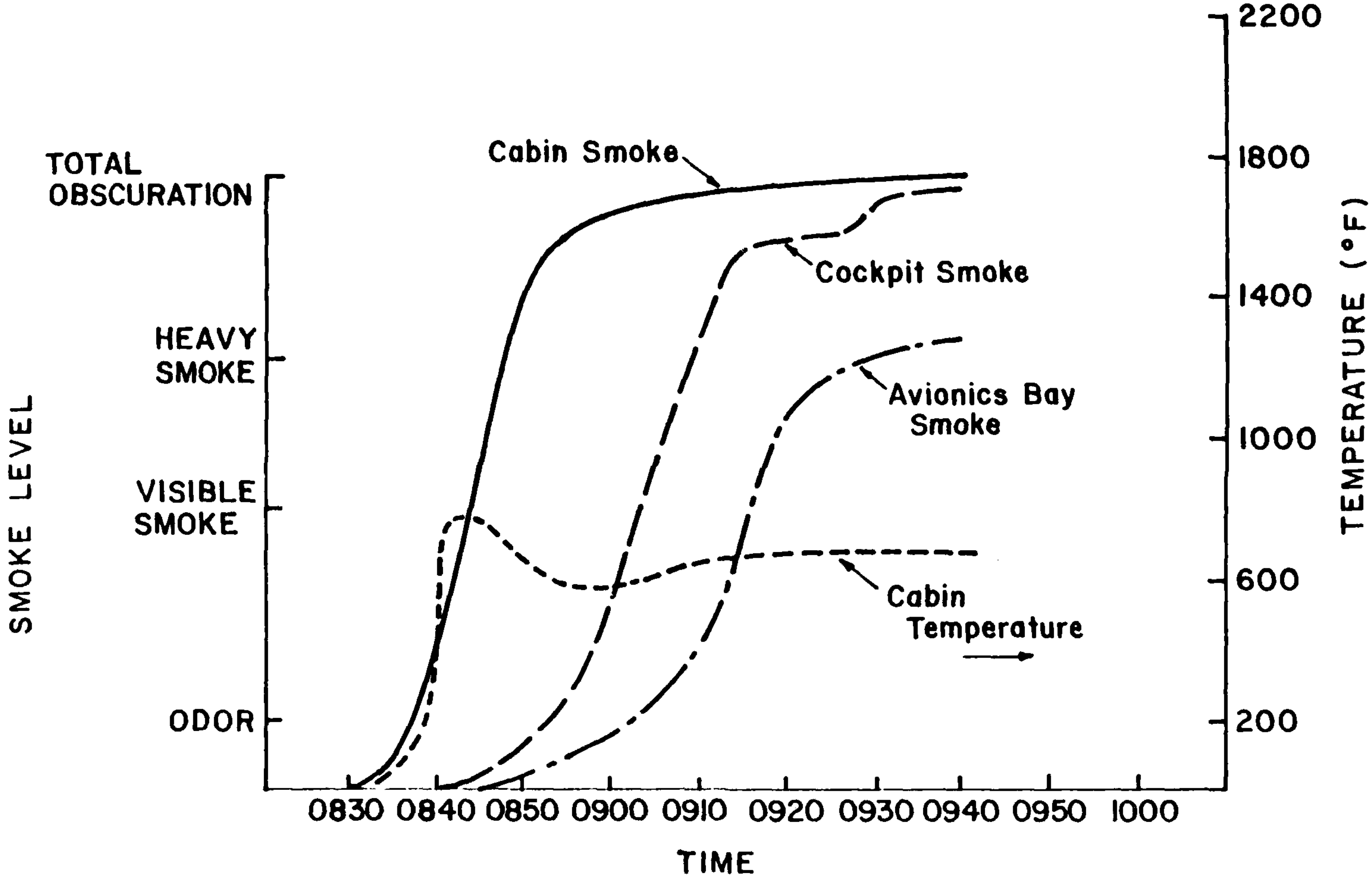

FIGURE 17. SCENARIO 12: SMOKE-TEMPERATURE SIGNATURES

Detection of the Fire. Initial detection of this incident was visual: smoke was seen issuing from the floor of the cockpit. Smoke was moving through the return air grilles which connected the cockpit to the avionics bay.

Localization of the Fire. The appearance of smoke issuing from the return air grilles in the cockpit led to the conclusion that the source was either electrical overheating or fire in the electrical compartment. This conclusion was not changed during the course of this incident ending in the crash and fire. There were no positive, corroborative indications (such as popped circuit breakers or failed equipment) to sustain the conclusion that the source was electrical. Subsequent investigation suggested that the fire began in the main cargo compartment at close to floor level on the left side of the aircraft. From there, smoke moved through the return air system into the Lower 41 area and from there, through the grilles into the cockpit.

Much later in the incident some attempt was made to examine the main cargo area and the Lower 41; by then heavy smoke was present in the main area and a lesser amount in the Lower 41. The crew theorized, wrongly, that an electrical fire in Lower 41 was generating smoke which passed through the cockpit (and by other routes) into the main cargo area where it accumulated. The reverse progression was, of course, the correct one.

Identification of Fire Severity. Since there was no investigation by the crew, the severity of the fire was never explicitly assessed. The persistent and growing smoke density was noted and late in the incident it was also noted that there was no other evidence of an electrical fire. Yet, it was never concluded that a severe fire existed in a location other than the electrical bay. The apparent conclusion (never actually stated) was that an electrical overheat or fire was inherently not extremely dangerous and that circuit breakers and load shedding would overcome the problem.

Evaluation of the Situation and Selection of Action. The source and the severity of the fire were never identified correctly, so no accurate evaluation could have been made. Because the crew persisted in the erroneous conclusion that it was an electrical overheat or fire, the only potentially effective action--immediate diversion to the nearest suitable field--was never taken. The Captain first--with the advice of his operations department--elected to return to his departure point, JFK. This entailed 45 minutes flight time. When it became apparent that the flight could not reach JFK, the Captain requested clearance to Boston's Logan Airport. The Captain, still under the misperception that the fire was electrical (and presumably not especially hazardous) passed a military airfield that was suitable and much closer than Logan. Further, an emergency was never declared although at this stage of the flight such a declaration would have had little effect. During the diversion to Logan, there was some confusion in the cockpit as to radio frequencies and there was some delay in locating the proper approach plates. These latter problems may have been simply poor crew procedure, or the result of rapidly increasing stress, or the result of some physical effects of the smoke-laden environment. These causes may also have worked in some interrelated way to produce less than appropriate responses. Another difficulty arising from crew performance occurred when the flight was on approach to Logan and the Flight Engineer executed equipment shutdown to unload the electrical system to only minimum required equipment. This shutdown removed yaw damping, but the Captain was unaware that the shutdown had been made. Just prior to the

crash, the aircraft was observed to go through extreme and erratic yawing probably because there was no damping. At about 35 miles from touchdown, the crew attempted to ventilate the smoke by opening a cockpit window. Because the location and source of this fire had been wrongly identified, this action only resulted in bringing more smoke into the cockpit and perhaps increased the rate of burning.

Conclusions. In this incident there are two crew-related events which were major contributors: the crew never attempted to establish the exact location and nature of the fire even though the initial evaluation of electrical overheat was never confirmed. The second contributor consisted of inappropriate decisions and responses. Some of these stemmed from the wrong identification and some appeared to be the result of less than standard crew performance. Specifically, when there was no confirmation of an electrical fire (loss of equipment function or circuit breakers popping) the crew should have initiated a more intensive analysis of the incident. Also, the Captain apparently concentrated too much on bringing the aircraft to a field at which his company had facilities. In view of the fact that the fire was never firmly established as electrical or as being in the Lower 41, the Captain should have given much greater emphasis simply to getting the aircraft on the ground.

It can be inferred that crew procedures and coordination were generally poor. The really critical problems occurred, however, only when the fire and smoke were well advanced and the resulting stress on the crew was extreme.

SCENARIO 12 - ACES ANALYSIS. The incident in this scenario began when an improperly packed container of nitric acid was placed aboard an all-cargo flight and not identified on the manifest. The acid spilled at 0830, triggering a hypergolic combustion. There were no sensors in the cargo compartment; smoke appeared at 0904 in the cockpit (by way of the "return air" grille) and smoke sensors in the avionics bay below the cockpit activated at 0910.

The ACES system in this situation would have provided a positive alarm of fire just a few minutes after ignition at 0830. The dual sensor logic would have sensed smoke and determined a rapid rate of rise by about 0834. The redline for heat would have been reset at that time and a smoke alert established. Heat would have been detected about two minutes later so that a positive fire alarm would have been established showing intense burning at about 0836. Since the actual event was first detected at 0904, the ACES system would have provided an additional 28 minutes in which the crew could react and take appropriate action.

More significantly the ACES system could have provided a positive alarm of an intense fire, and given an exact location. Throughout the incident as it occurred, the crew persisted in the conclusion that it was heavy smoke being producted in the avionics bay because smoke appeared to be coming from that area. They persisted also in the belief that the source of smoke was not an active, intense fire; but rather an electrical overheat that could build to an active fire. This belief was maintained in spite of the fact that there was no direct evidence from any electrical component. This erroneous interpretation was continued even after smoke had been seen in the cargo compartment--the conclusion being that it was spreading through the return air system to the cabin. (Actually, of course, the exact reverse of what was happening.)

The real benefit of the ACES then would have been an exact and reliable location of the event and a reliable determination of its severity. The fact that ACES would have given almost a half-hour earlier warning is almost incidental in this scenario. The crew's actions based on wrong--but somewhat credible--diagnoses could have been successfully corrected even if the ACES information had not been received until 0904--the time at which smoke was actually seen. At that time there were closer, suitable airfield alternates both civilian and military; but using the wrong diagnosis, the crew elected to attempt to return to JFK.

In the fire narrative, the evidences of combustion in the avionics bay as well as the cockpit are described. The ACES system would have sensed and processed these, but that would probably have had little effect on the outcome. The most important aspect of ACES for this situation is the location of a sensor pair in the cargo area that would have provided reliable location and severity information in a timely way.

TABLE 12. SCENARIO 12 - TIMELINE SUMMARY

ACES BENEFIT	System alarm at approximately 0836		Early knowledge of exact location and intensity of fire		Earlier diversion to to an alternate airfield				
ACTUAL RESPONSE			Conclude there is an electrical fire; begin diversion	Request ATC clearance	Change to Logan	Begin landing preparations	Plan for short final	Situation worsens	Loss of yaw damper
ACTUAL DETECTION			Crew visual/ smell	Same	Crew visual/ smell and cargo smoke	Same	Confirmed detection by Flight Engineer	Same	Same
CIRCUMSTANTIAL EVIDENCE AVAILABLE			No circuit breakers trip	No breakers; smoke, concentration increasing & traveling	No breakers; temperature/ smoke increasing	Same	Same	Same	Same
COMBUSTION EVIDENCE AVAILABLE		Increasing smoke; slowly increasing temperature	Smoke; heat	Same	Same	Same	Same	Same	Same
EVENT	Acid spills	Fire breaches packing box	Smoke detected	Decision to return to JFK	Cleared to JFK; don masks	Plan Logan approach	Open window	Electrical system shutdown	Crash
TIME	(0830)	(0856)	(0904)	(0906)	(0910)	(0914)	(0927)	(0935)	(0940)
FLIGHT PHASE	Cruise	Cruise	Cruise	Cruise	Descent	Descent	Descent	Descent	

SCENARIO 13 - ACCIDENTAL IGNITION BY PASSENGER.

SCENARIO 13 - DESCRIPTION. A wide body twin-jet aircraft was operating nonstop from Los Angeles International to Boston's Logan International as the late night "redeye." The flight crew consisted of Captain and First Officer; in the cabin there were six Attendants. Departure was scheduled for 2230 Pacific Time, but was delayed due to the late arrival of the inbound aircraft. Take off occurred at 2335 after normal pre-flight checklists. The crew were all experienced in type and had flown together previously. The passenger load was light with only 80 passengers on board. As is customary on late night transcontinental flights, beverage service was short and the cabin lights were extinguished at 0030. Passengers who wanted to read had to use their individual reading lights.

At 0045 a passenger in the left side window seat in the last row of first class decided to check his hotel confirmation. He attempted to illuminate his reading light, but it would not work. With his attache case open on his lap, he struck a match to provide sufficient light to read. The entire book ignited, and he dropped it into his case where numerous loose papers immediately caught fire. The passenger panicked and shoved the case towards the vacant seat to his right. This action opened a can of lighter fluid in the attache case which leaked out and quickly spread the fire to the seat materials and the clothing hung on the hooks attached to the bulkhead. At this time, the aircraft was 120 miles east-northeast of Las Vegas at flight level 330.

The fire effectively blocked the aisle at a time when all of the Attendants were in the aft, coach section of the aircraft. The Senior Flight Attendant heard the commotion and looked up to see the flames. She immediately ordered one of the other Attendants to notify the cockpit on the intercom. She then located a hand fire extinguisher in the aft compartment and went forward to fight the fire. The Captain received notification on the intercom at 0046.

Upon receiving notice, the Captain declared an emergency to ATC and donned his oxygen mask. He also directed the First Officer to take the hand extinguisher from the cockpit, don his smoke mask and oxygen bottle and take command of the firefighting. At 0048 the First Officer exited the cockpit into the first class compartment which was rapidly filling with smoke.

The Captain contacted ATC at 0050, declared an emergency and requested immediate clearance to McCarran Field in Las Vegas. He requested AFRR and emergency medical teams to meet the plane. He received immediate clearance to descend and was given vectors direct to McCarran.

The Captain then retrieved the Flight Crew Operations Manual (FCOM) and looked up the checklist for in-flight fires. He took the necessary actions.

The First Officer found that the flames had been almost completely extinguished by the first fire extinguisher deployed by the Senior Flight Attendant. There appeared to be some continuing smoldering which was generating smoke. He discharged his extinguisher at the smoking area.

The passenger who had started the fire and two others sitting on the aisle in the first row of coach had been injured. The First Officer ordered all passengers from first class and the first 10 rows of coach to move aft to vacant

seats. He directed the Senior Flight Attendant to apply first aid to the injured. He then returned to the cockpit, donned his oxygen mask and reported to the Captain.

At 0056 the aircraft was in a rapid descent towards Las Vegas when the Cabin Crew reported that the smoke was starting to cause problems. The First Officer reviewed the smoke elimination procedures in the FCOM and told the Captain he had the option of opening the left forward and aft doors once they were below 10,000 feet, provided that the fire was completely extinguished.

At 0058 the Cabin Crew reported that the fire was completely out, but that smoke persisted in the cabin and was causing breathing and eye irritation problems among the passengers. The Captain directed the First Officer to brief the passengers via the public address for both the door opening and an emergency evacuation after landing. At 0109 the aircraft had descended through 10,000 feet, and the Captain slowed the rate of descent to 2,000 ft/min and ordered the doors opened. This helped clear the smoke and prevent further passenger injuries from smoke inhalation.

ATC gave clearance for an ILS approach to McCarran at 0105 and notified the crew that ARFF and EMTs were standing by. The Captain then executed a safe landing with a maximum effort stop and the passengers exited by the evacuation slides. AFRR personnel entered the aircraft and found the fire had been extinguished.

SCENARIO 13 - FIRE NARRATIVE. This fire was caused by the accidental ignition of a book of matches, which, when dropped by the passenger, ignited loose papers in his briefcase. The fire escalated further when it contacted liquid lighter fluid and spread quickly to seat materials. The burning materials generated smoke primarily in the first class compartment. The fire was totally extinguished within five minutes by use of hand-held fire extinguishers.

SCENARIO 13 - PROBLEM ANALYSIS.

Detection of the Fire. The detection of this incident occurred virtually simultaneously with the start of the fire. The Cabin Crew was aware of the flames as soon as the can of lighter fluid ignited.

Localization of the Fire. Localization also occurred simultaneously with ignition. There could be no question as to its location.

Identification of Fire Severity. While the record of this incident shows no explicit assessment of severity, the immediate declaration of emergency and the order to the First Officer to take charge of attacking the fire, suggest that the Captain assessed that it was a potentially severe fire. This was apparently a correct assessment.

Evaluation of the Situation and Selection of Action. The situation was correctly evaluated as having a potential for reaching severe, tragic proportions. The actions which began with declaring an emergency and initiating emergency diversion included direct attack with extinguishers and movement of passengers away from the fire site. All of the actions were appropriate and correctly implemented. The most significant event in this incident was the Captain's prompt emergency declaration and diversion.

Conclusions. This incident while an unusual and perhaps very unlikely one, was evaluated and handled in a prompt and efficient manner by all of the crew. By initiating an emergency diversion immediately upon detection, the Captain maximized the probability of a successful, safe landing. He also initiated a prompt and eventually successful attack on the fire. The door opening for cabin ventilation proved to be successful and the emergency evacuation was completed with no problems.

SCENARIO 13 - ACES ANALYSIS. This scenario involves accidental ignition of a fire by a passenger in the passenger compartment. The description is of an event involving lighter fluid, but it could have been pressurized hair spray, a butane lighter or lighted smoking material.

The ACES system in its basic form would not include sensors in the passenger compartment: the crew and passengers present in the compartment constitute a sensing and severity evaluation system at least equal to (or perhaps even faster than) the projected ACES hardware. It is within the overall ACES concept, however, to process and respond to this human sensor input in much the same way that automatic sensing is dealt with. The human-sensed information could be entered manually and the ACES would supply all of the appropriate emergency procedures and would have reset its own sensing system in recognition of the on-board fire.

In this incident the rapid detection and diagnosis that is critical for most in-flight fires is of lesser importance than the support ACES provides in emergency procedures and the change in sensitivity of the entire ACES system. This incident was quickly defeated and the consequences were not serious. A similar situation could be imagined in which the support from the ACES system would have been a more critical input.

TABLE 13. SCENARIO 13 - TIMELINE SUMMARY

ACES BENEFIT	Display of appropriate emergency procedures							
ACTUAL RESPONSE	Hand extin- quisher; notify cockpit	Declare emergency; FE to help fight fire; 2nd extinguisher	Request clearance to Las Vegas	Set A/C	Review FCOM; decision to open doors	Doors opened		
ACTUAL DETECTION	Visual/ auditory	Intercom	Flight Engineer visual	Confirmed	Attendants	Confirmed		
CIRCUMSTANTIAL EVIDENCE AVAILABLE	Flame	Notification by Attendants	Confirmed fire	Same	Same	Same		
COMBUSTION EVIDENCE AVAILABLE	Quick heat rise	Smoke; heat	Same	Same	Smoke	Same		
EVENT	Passenger lights match	Captain notified	ATC contacted	Execute fire checklist	Smoke problem report	Order to open doors	Touchdown	Emergency evacuation
TIME	(0045)	(0046)	(0050)	(0052)	(0056+)	(0058)	(0107)	(0108)
FLIGHT PHASE	Cruise	Cruise	Cruise	Descent	Descent	Descent	Landing	Parked

CONCLUSIONS

The purpose of this study was to conduct a technology assessment to determine whether the feasibility exists for the FAA to support the development of a computer-based cockpit system to assist aircraft command in emergency situations (ACES). The several analyses that were conducted in this study highlighted numerous benefits arising from the use of an ACES system which lead directly to the conclusion that an ACES is both feasible and a desirable addition to commercial transports.

The activities of the present study were structured around answering four questions posed by the Statement of Work. The specific conclusions with respect to each of these questions will now be presented followed by a discussion of considerations related to the implementation of an ACES.

WHAT INFORMATION IS NEEDED TO LOCATE AND MONITOR FIRE AND SMOKE SOURCES?

The circumstances surrounding the handling of in-flight fire and smoke events were examined as a four step process--detection, localization, identification and evaluation/action. The analysis of actual incidents led to the conclusion that the major difficulties in actual fire events were primarily in the first three processes. Fires often went undetected until they had had time to grow and spread significantly. Even when initial detection evidence was available from sensors or human observation, localization of the fire's source and identification of the severity of the incident were often delayed or inaccurate. The failure of the flight crew to assess correctly the type and severity of a fire/smoke event was a major factor in the observed delays in taking appropriate action. These delays resulted in less available time in which to make a safe landing.

The key to successful management of in-flight fire and smoke events is the detection of the fire early in its development. The essential information can be derived from remote sensors which produce analog outputs. These outputs, when monitored by an "intelligent" computer program, can yield trend information which permits both the early detection of a fire and the discrimination of real from false events. It is concluded that sensor batteries of co-located aerosol (smoke) and temperature (heat) sensors will provide the best information.

This study identified many candidate locations in which sensors could be placed within the fuselage of a transport aircraft. The scenario-based analysis of the ACES permitted these areas to be classified according to their priority for sensor installation. The areas with the highest priority, i.e., those in which it is concluded that sensors should be installed include the following four areas. These areas contain sensors of some kind in most existing aircraft.

CARGO COMPARTMENTS. The inaccessibility of the cargo holds, the variety of combustibles they can contain and the problems experienced in cargo areas indicate the need for a battery of heat and smoke sensors.

LAVATORIES. The relatively high frequency of fire incidents in lavatories suggests the need for a sensor battery installation.

AVIONICS BAY. The criticality of the components housed in the avionics bay necessitates a maximum protection approach. Hence, a heat and smoke battery of detectors appears warranted. This reasoning also applies to the areas behind the instrument panel in the cockpit.

LOWER LOBE GALLEYS. Galleys located below the passenger deck are similar in nature to cargo holds. Even though occupied for some of the time during a flight, these galleys should be considered high risk areas given the numerous combustion sources and relatively poor accessibility.

A second group of areas within the fuselage is characterized by a moderate problem potential. These areas may be candidates for the installation of sensors if cost/benefit analyses indicated they were warranted. Locations included in this group are:

CHEEK AND 'TTIC.The potential for combustion in cheek and attic areas would suggest the need for remote sensing of some type. Continuous filament (line-type) heat sensors may be the best approach for cheeks and unoccupied attic spaces. Both smoke and heat sensors appear to be necessary in those attic spaces to be used as crew rest areas. The extremely large volume in cheeks and attics suggests a need for sensors, but cost/benefit analyses should be done.

MAIN DECK GALLEYS. These galleys are the most frequently reported site of fire/smoke incidents. Even though many of these are of limited severity, the total frequency suggests a study of the use of ACES sensors. In such a study, the accessibility of these galleys to human sensing must be considered. By way of comparison, the rapid response and resistance to false alarms inherent in the ACES intelligent sensors must also be considered. A practical and cost-effective implementation can be achieved.

APU AND AIR CONDITIONING PACKS. These units are already monitored in some manner. The trade-offs associated with upgrading their sensors to the ACES level of sophistication would have to be examined.

CLOSETS AND STORAGE BINS. Closets and storage bins within the passenger cabin can contain a variety of flammables. Fires within these compartments can grow undetected even though many human "sensors" are nearby. The absence of incidents would argue against sensing, but the potential for passenger involvement and the proximity of passenger service centers would suggest consideration of detector installation. Again, an analysis of cost and overall benefit is needed.

The third group of locations would appear not to warrant sensor installation. This group includes:

COCKPIT OPEN AREAS. The continual presence of a crew member in the cockpit's open areas greatly reduces the need for sensors.

PASSENGER CABINS. The technical problems involved in remote sensing of the passenger cabin appear to outweigh any potential benefits. The passengers and crew can provide sufficient early warning.

In addition to sensor information and alerting by crew and passengers, it is concluded that "circumstantial" evidence can also be used productively to

enhance the effectiveness of an ACES system. This information would include data on flight dynamics, circuit breaker status and electrical and hydraulic loads.

IS THE SENSING CAPABILITY AVAILABLE OR ATTAINABLE?

All of the information identified by this study as having potential utility for an ACES system is well within the state-of-the-art. Smoke and heat sensors using existing technology can be engineered to produce the analog outputs required by the ACES configuration. The "circumstantial" data are readily available on the present and contemplated aircraft digital data buses. It is therefore the conclusion of the present study that the input information needed to support an ACES system for the management of in-flight fires is available or easily obtainable and is not a limiting factor in either the development or deployment of an ACES.

WHAT COURSE OF ACTION CAN BE EMPLOYED IN REACTION TO THE SENSED INFORMATION?

The ACES configuration assessed by this study uses sensed information as input to an expert system which supports decision-making. The software attempts to discriminate real from false alarms, localize the fire or smoke and identify the severity of the incident. It also activates appropriate warnings for the crew and presents them with information upon which to select and deploy countermeasures.

The analysis of the in-flight fire problem led to the conclusion that the current major sources of difficulty were fire detection, localization and identification. There were also problems in locating and retrieving procedural checklists. Once these steps were successfully performed, the indicated course of action in all cases of confirmed or possible fire or smoke incidents was to terminate the flight at the nearest suitable airport, deploy suppression efforts if available, and execute smoke elimination procedures if warranted. The analytic results as well as the opinions of the airline and airframe companies contacted suggested no other response to an in-flight fire than an immediate landing. The results also did not uncover any significant problems with the prescribed emergency checklist procedures even though some difficulty in locating and using them contributed to the severity of some in-flight fire incidents.

It is concluded that an ACES system design effort should focus on the rapid detection of fires, the discrimination of real from false alarms and the promotion of correct and timely decision-making by the flight crew. The essential response in the case of an ACES-confirmed fire, or the inability of the ACES to resolve the available information within a reasonable time is the immediate, safe termination of the flight.

When the ACES is able to determine that the condition sensed is a sensor failure, the ACES should have the capacity to alert the crew and reconfigure to continue sensing without the failed unit. The operating policies of the individual airlines should then dictate the specific system response which could range from terminating the flight to holding the entire failure and reconfiguration transparent to the crew.

The consideration of reaction to sensed information must also be concerned with flight crew workload in two ways. First, the workload level at the time the ACES presents the information must be assessed. This level will determine the ability of the crew to react to the ACES warning. It is, in essence, a queuing theory approach to pilot workload and addresses the capacity of the crew to deal with the next task presented, i.e., the ACES warning.

Second, a potentially relevant aspect of workload is the incremental workload presented by the ACES stimulus. In addition to responding to the ACES information, the crew must fly the aircraft and manage any other problems which have arisen. Even if the ACES presents important information in a timely manner, it may be ineffective if it creates an overload situation.

Theoretically, workload is an issue of concern with respect to an ACES system. Clearly, care must be exercised in any future ACES design effort to insure that the ACES configuration is compatible with the total set of tasks the crew might be called upon to perform at the time an ACES warning is generated. Within the context of the present study, however, it was concluded that excessive workload was neither a major part of the identified problem of in-flight fires nor a significant factor in determining the feasibility of an ACES system.

The conclusion that crew workload is not a major concern for ACES arises from a careful review of the actual in-flight fire incidents collected for this study. To be sure, excessive levels of workload were experienced during these incidents. However, the origins of this workload were generally errors by the crews in interpreting signs of the fire and problems in locating and accessing the correct procedural checklists. For example, in Scenarios 1 and 12, flight crew workload reached excessive levels because the crew unreasonably delayed accepting and responding to the signs of fire which had been accurately presented. These delays allowed the fires to reach a level of seriousness which would not have been experienced while the aircraft was still airborne if the crew had diverted to the nearest suitable airport at the first indication of a problem.

The ACES as configured for this study was designed to reduce crew workload by collecting and analyzing data and applying expert rules without the intervention of the crew. It is also intended to present appropriate checklists and status displays automatically, thereby further reducing the effort required of the crew. These benefits, however, can only be fully realized if the crew has faith in the ACES and responds confidently and swiftly to its warnings. It is reasonable to conclude that the required trust will be achieved if an ACES implementation is accomplished with a level of reliability that is consistent with other well accepted avionics systems.

<u>WITHIN CONSTRAINTS OF ANTICIPATED COCKPIT TECHNOLOGY FOR FUTURE COMMERCIAL TRANSPORT AIRCRAFT, CAN THIS INFORMATION BE COMPUTERIZED AND RETRIEVED IN A FAIL-SAFE OR FAIL-OPERATIONAL MANNER?</u>

There is virtually no doubt that anticipated cockpit technology for future large transport aircraft can support an ACES as envisioned by this study. The industry plans for increased use of digital data buses and integrated avionics processors running compiled programs written in the Ada language provide an ideal setting for the installation of an ACES. Moreover, there would appear to

be more than adequate processor capacity to support an ACES system operating at an efficient rate of information updating.

It is also concluded that an ACES can be easily and productively integrated into the existing master warning concept for crew alerting. The present "glass cockpit" includes two displays for monitoring all aircraft systems and the associated computational support. This provides an appropriate interface between the crew and an ACES system. Thus, cockpit hardware changes with respect to information retrieval from an ACES should not represent an obstacle to further ACES system development.

The types of input information required for an ACES processor to reach "intelligent" decisions in a reliable manner are typically available on the current generation of transports. Engineering sensors to produce an analog output so that heat and smoke level can be tracked over time is not a problem. The accurate transmission of the sensor data and any other inputs required by the ACES processing algorithms is assured by the inherently robust design of digital data buses structured according to ARINC specifications.

Perhaps the greatest potential source of low reliability for an ACES system would be the decision rules implemented in the software. If these rules are not carefully designed, excessive false alarms or unwarranted delays in issuing a warning could result. The types of algorithms required are primarily trend detection for determining positive slope, pattern recognition for detecting fire signatures and failed sensors, and Boolean logic to deduce a fire situation from a variety of input signals. Each of these types of decision rules has been extensively studied and used in systems analogous to an ACES. It is therefore reasonable to conclude that software can be written to achieve greatly improved in-flight fire management performance. Further, virtually fail-safe operation can be achieved by built-in diagnostic routines and the adoption of conservative responses to ACES alerts and alarms.

IMPLEMENTATION.

The conclusion that an ACES is feasible and well within the state-of-the-art leads to the additional finding that a detailed design effort is warranted. This design study would have to address the microscopic issues highlighted by the present effort. In order to yield the best possible design, it is believed that the next effort should be multi-disciplinary in nature and cover at least:

SENSOR TECHNOLOGY. A careful examination of the alternative aerosol and temperature sensors capable of producing analog outputs is needed. Both spot and line-type sensors should be covered. Sensor response patterns, reliability, maintainability and cost should be considered.

FIRE SIGNATURES. Signatures for the most likely in-flight fire events have to be identified from experimental input. These signatures should focus on the patterns produced by each type of fire on the designated types of sensors.

AMBIENT SIGNATURES. In order to function effectively, the ACES must be able to distinguish real fire signatures from the variety of ambient conditions likely to be experienced during transport operations. The best way to accomplish this is to build a normative data base of the ambient conditions and

the situations which produce them. This data base could be produced by installing sensor batteries in line aircraft and monitoring their outputs over an extended range of flying conditions. These data could be augmented by controlled experiments with actual aircraft to simulate conditions of interest which were not experienced during the on-line data collection.

FMEA/CIL AND HAZARD ANALYSES. A failure modes and effects analysis (FMEA) and a critical incident list (CIL) should be prepared for a representative set of aircraft types. These analyses will support a detailed fire hazard analysis which will identify and quantify the specific threats the ACES must be designed to address.

ALGORITHM DEVELOPMENT. Statistical and logical decision rules must be developed based on the detailed FMEA/CIL analyses and the hazard analysis. These will be used as input to software development.

HUMAN FACTORS ANALYSIS. The detailed system design would have to be guided by an allocation of functions between the processors and the crew. This allocation would arise from a human factors analysis. Among the issues to be addressed would be when and how to alert the crew and when to keep the activities of the ACES transparent. Detailed design specifications for the content of any warning messages to be displayed would also be needed. Further, the cost-effectiveness of a "line select" function to permit the crew to accomplish checklist items automatically by acknowledging an ACES request to take action should be explored.

SOFTWARE DEVELOPMENT. The identified algorithms and warning displays would have to be implemented in Ada code to run on the new 32 bit avionics processors. Associated software for transmitting sensor signals on the digital data bus and retrieving non-sensor data from the bus would also be required.

As part of this study, individuals in the aircraft and airline industry were contacted and exposed to the concept of an ACES. The assistance given by these individuals and organizations as well as their strong expression of interest suggest that a properly designed and reasonably priced ACES system for new aircraft would be positively received. There also appeared to be a strong sentiment that the introduction of an ACES system would be facilitated if the FAA or other governmental agency funded the required developmental research and promoted the system as a cooperative government/industry program rather than as an airworthiness regulation.

Finally, the efforts surrounding the present study led to a conclusion which relates to aviation fire safety in general as well as to ACES implementation. Many of the actual in-flight fire incidents examined involved an apparent lack of appreciation by the crew of the fire generation process and of the potential hazard of even a limited in-flight fire. This was manifested in protracted attempts to confirm the existence of a fire or to suppress it before taking immediate steps to terminate the flight. At the outbreak of a fire, flight crew behavior appears to be analogous to the typical homeowner who stays behind to fight a blaze which is already out of control or to retrieve personal belongings. This behavior can most probably be attributed to knowledge deficiencies concerning fire safety. It is therefore not unreasonable to conclude that some of the incorrect decision-making by flight crews arises from the same inadequate knowledge about fires.

In order to insure the maximum effectiveness for an ACES and, in fact, for aviation fire safety in general, enhanced training of flight and cabin crews in the fire generation process should be explored. This would augment existing efforts which are focused primarily at fire suppression activities. The additional understanding promoted by training of this type would provide the background needed to establish appropriate priorities after a fire is detected.

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